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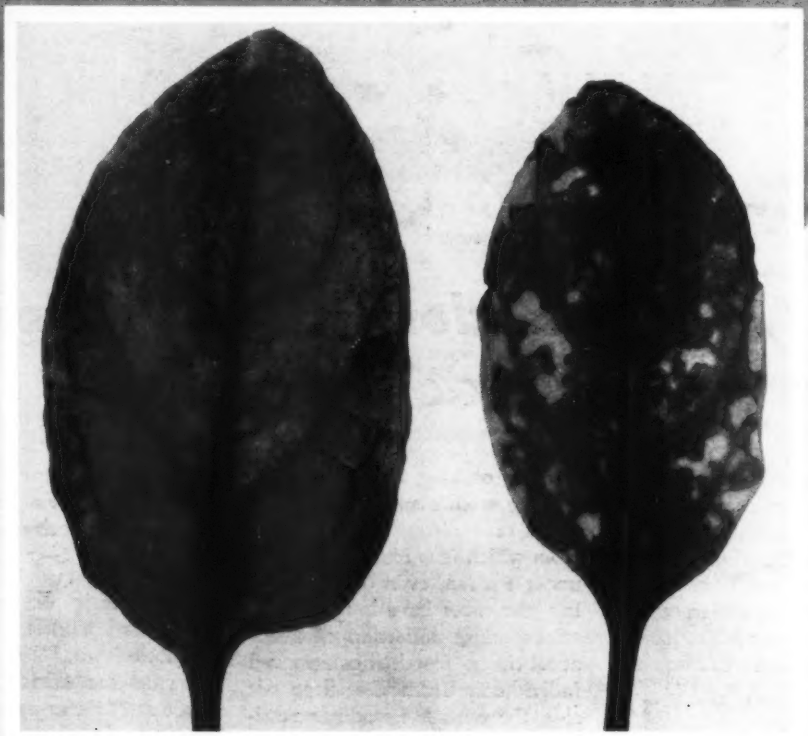

Vol. 6, No. 1 May 1956

How Plants Respond to Air Pollution

(See page 7)

STACKS

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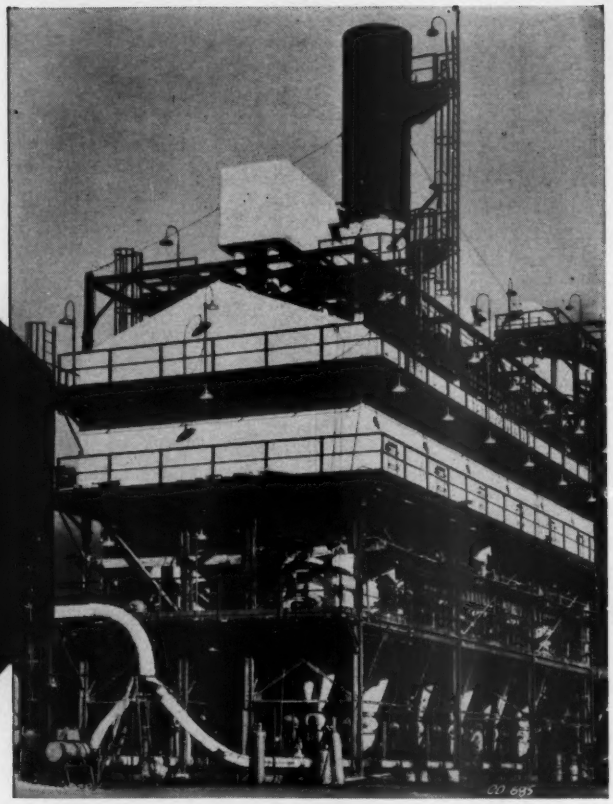

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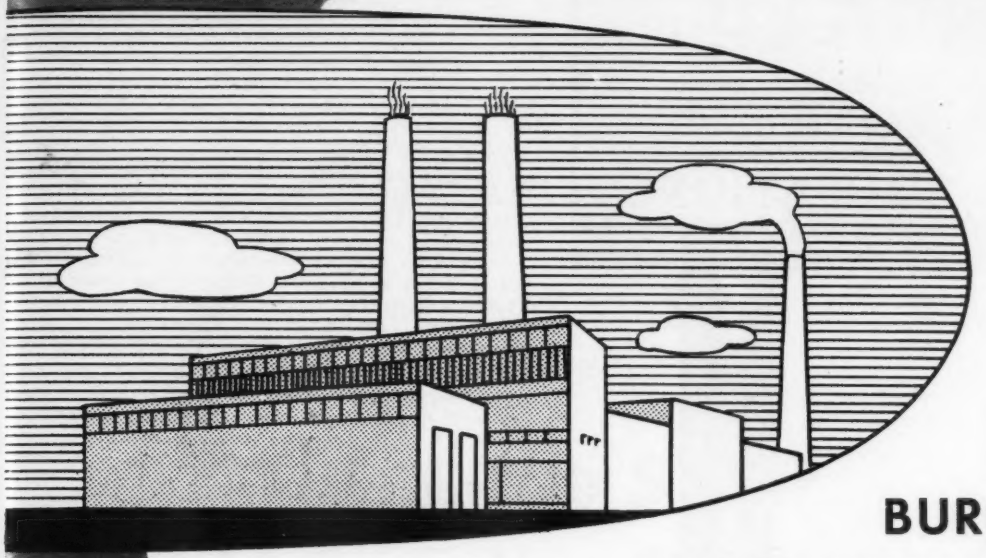

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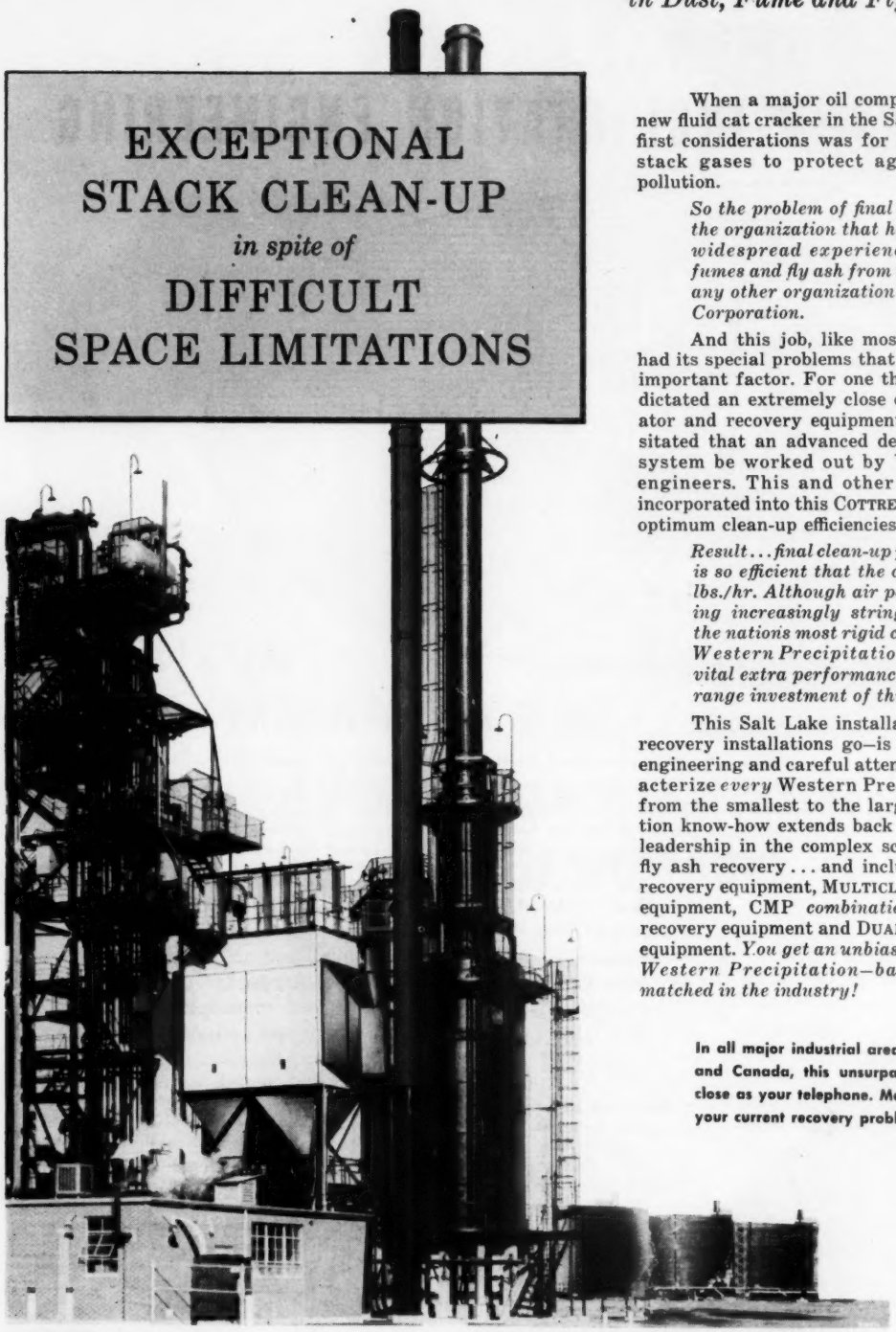

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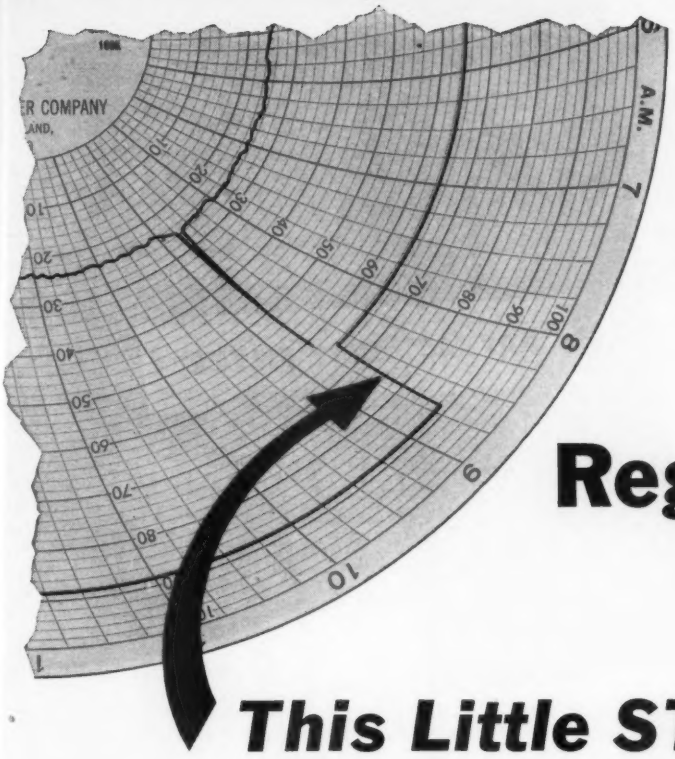

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The Editor welcomes writers interested in air pollution problems and encourages them to use the pages of this journal for the expression of their opinions. But neither he nor the Association assumes responsibility for the validity of the opinions expressed herein.

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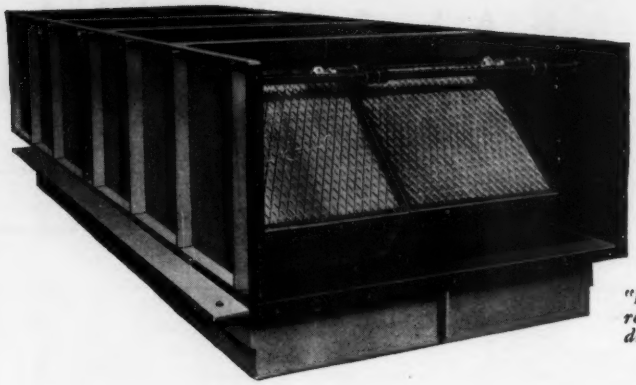

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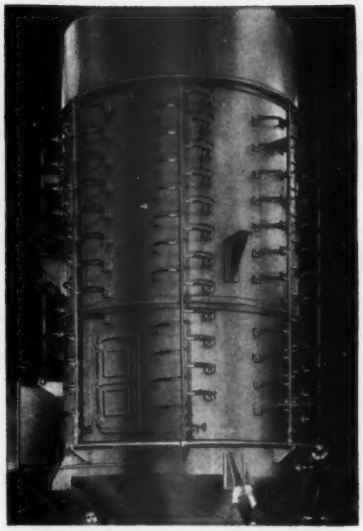

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Response of Plants to Air Pollution

JOHN T. MIDDLETON

University of California
Riverside, Calif.

The effects of air pollution upon vegetation have been studied for more than a century. Past interest centered particularly on smoke and fumes from industrial atmospheric wastes. M. D. Thomas[12] ably reviewed this subject and reported that gases are more important than solids or liquid aerosols in causing injury to plants and that the principal phytotoxicants were sulfur dioxide, fluorides, and halogens. More recently, in the past decade, a new class of airborne toxicants has been discovered and identified by the term "oxidant." The writer first discovered oxidant damage to leafy vegetable and field crops near Los Angeles, California, in 1944. This is quite different from the type of damage known to be associated with fluorides and sulfur dioxide. Its symptoms were described by Middleton *et al.*[10] and consisted of a silvering, bronzing, and necrosis, principally on the lower leaf surfaces, on a variety of agricultural crops and weeds (Fig.1). Some aspects of the patterns of damage were described by Noble[11] while Bobrov[1,2] has reported and figured some of the anatomical changes.

Plants are most seriously damaged during periods of aggravated air pollution, when visibility is reduced and human distress is reported. Annual leafy vegetable crops, forage crops and grasses, and field and glasshouse-grown ornamentals and flowers are among the most seriously damaged plants. The area affected and the monetary loss to annual crops alone have continued to increase in extent and severity, such that current annual losses have exceeded one-half million dollars since 1949, when they were first estimated to be approximately $480,000 to 11 crops in Los Angeles County alone. In 1953 damage to this same area exceeded $3,000,000. The area affected in southern California consists of a more or less triangular zone extending from the Mexican border on the south to the Ventura coastal plain on the north and eastward approximately 80 miles to Banning. The progressive expansion of the polluted air mass responsible for plant damage is graphically portrayed in Fig. 2. Plant damage surveys now show that a great variety of field, fruit, and vine, ornamental, and vegetable crops suffer serious loss.

Damage of the same kind found in the Los Angeles coastal basin was first observed by the writer in the San Francisco Bay area in 1950. The variety of crops affected and the area involved have increased in number and size with mounting annual dollar loss to agricultural ventures in coastal central California. These observations suggest that plant-damaging pollutants identifiable as airborne oxidants may be expected to encroach upon rural areas associated with urban growth and development.

The toxicants responsible for this specific type of plant damage have been shown to be the reaction products resulting from the oxidation of the hydrocarbons present in refined petroleum and oxidants such as ozone and oxides of nitrogen in sunlight. This discovery was made through a cooperative research project of the University of California Citrus Experiment Station, Riverside; California Institute of Technology, Pasadena; and the Los Angeles Air Pollution Control District; and was reported by Haagen-Smit *et al.*[3]. Injury typical of that which occurs naturally in the Los Angeles coastal plain and the San Francisco Bay area can be reproduced under controlled conditions by exposure of plants to the oxidation products of ozonated unsaturated hydrocarbons. Injury to plants resulting from exposure to ozonated gasoline is indistinguishable from that produced by the ozonation of 1-*n* hexene under the conditions of experimentation provided at Riverside.

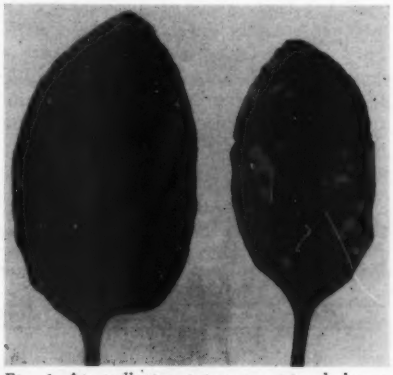

Fig. 1 Air pollution injury to spinach leaves attributable to oxidized hydrocarbons. L., silvering found on the lower leaf surface. R., necrosis and chlorosis of the upper leaf surface developed as a result of desiccation of the lower leaf tissue.

As a result of mounting annual loss to the important vegetable, field, vine, and citrus industries of California, an air pollution research activity centered at the University of California, Citrus Experiment Station, at Riverside was recently initiated for the purpose of determining the effects of air pollution upon plants, methods of protecting plants from air pollution injury, and through the response of plants learn more about the identity of the airborne phytotoxicants.

Plants are exposed in glazed 6-ft.^{3} fumigation chambers located out-of-doors. The air introduced into the chambers passes through beds of activated carbon to remove all phytotoxic oxidants. Controlled air temperature and relative humidity are maintained by recycling through conventional air conditioners. Air residence time is regulated by controlled input of new, unrecycled air. Ozone is generated in a Berthelot tube from compressed oxygen; the amount of ozone introduced into the fumigatorium is regulated by rate of oxygen flow and tube field voltage. Hydrocarbon vapor is dispensed from a glass tube supplied by a constant head reservoir. The amount is regulated by displacement with compressed nitrogen and temperature of the liquid hydrocarbon. Ozone and hydrocarbon are first brought together in a glass reaction tube which is exhausted directly into the chamber. Oxidant concentration is measured by determining the iodine released from potassium iodide buffered with Sorenson's reagent. Desired oxidant levels are secured by varying the ratio of ozone to hydrocarbon and air residence time.

Plants vary in their susceptibility to the reaction products from the oxidation of hydrocarbons. Among the more sen-

[1] Bobrov, R. A., "The Anatomical Effect of Air Pollution on Plants," *Proc. Sec. Natl. Air Pollution Symposium* 129-34 (1952).

[2] Bobrov, R. A., "The Leaf Structure of *Poa Annua* with Observations on Its Smog Sensitivity in Los Angeles County," *Amer. Jour. Bot.* **42**, 467-74 (1955).

[10] Middleton, J. T., Kendrick, J. B., Jr., and Schwalm, H. W., "Injury to Herbaceous Plants by Smog or Air Pollution," *U. S. D. A. Plant Disease Repr.* **34**, 245-52 (1950).

[11] Noble, W. M., "Pattern of Damage Produced on Vegetation by Smog," *Agric. Food Chem.* **3**, 330-32 (1950).

[12] Thomas, M. D., "Gas Damage to Plants," *Ann. Rev. Plant Physiol.* **2**, 293-322 (1951).

[3] Haagen-Smit, A. J., Darley, E. F., Zaitlin, M., Hull, H., and Noble, W., "Investigation on Injury to Plants from Air Pollution in the Los Angeles Area," *Plant Physiol.*, **27**, 18-34 (1951).

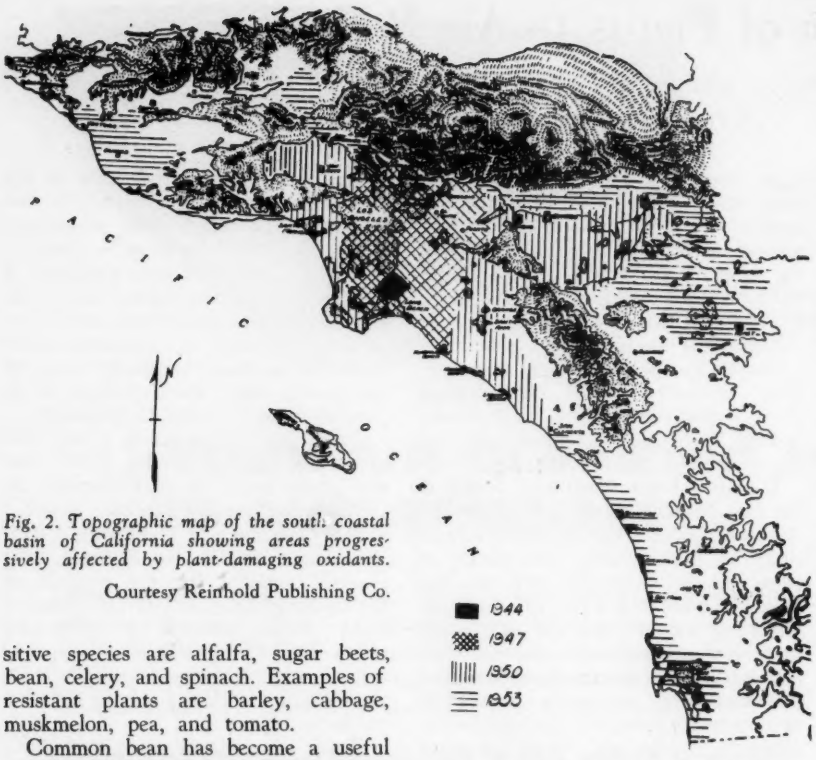

Fig. 2. Topographic map of the south coastal basin of California showing areas progressively affected by plant-damaging oxidants.

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sitive species are alfalfa, sugar beets, bean, celery, and spinach. Examples of resistant plants are barley, cabbage, muskmelon, pea, and tomato.

Common bean has become a useful test plant for measuring the mechanisms of damage and some of the effects of oxidized hydrocarbons upon the life processes. The pinto bean has been selected for most of this work since suitable experimental material can be produced from seed in about 2 weeks and the leaves are extremely sensitive to damage[8]. The paired primary leaves provide a substrate uniformly susceptible to the toxicants and suitable to numerical assignment. The extent of injury is estimated and assigned a value based on the percent leaf area damaged. Values range from 0 representing no injury to 10 representing complete damage.

The effect of age of pinto bean on susceptibility of leaves to the toxicants is given in Table II. These data show that the young, immature leaves are not as susceptible as those that are mature and fully expanded, and that the primary leaves are uniformly susceptible to damage 2 wk. after emergence and remain so for at least 3 additional wk.

The varieties of a species differ in their response to given levels of oxidant. The susceptibility of bean varieties grown in soil in 6-in pots and exposed to 0.28 ppm. oxidant for 7 hr. is presented in Table I. Work is current testing existing vegetable, vine, and flower varieties for the purpose of providing suitable material for crop production in the polluted air basins of California.

It has been found in preliminary experiments conducted in cooperation with S. J. Richards of the Department of Irrigation and Soils, University of California at Riverside, that bean plants grown with an adequate water supply of approximately 300 cm. moisture tension, are more susceptible to damage than those grown with a less adequate supply of approximately 2 atm. of tension. It is possible that some protection can be afforded agricultural crops during short periods of aggravated air pollution provided the agriculturist is given the opportunity of exercising his option to withhold water for the period of expected pollution damage.

Controlled fumigations have shown that the severity of plant damage varies with the air temperature under which the crop is grown prior to fumigation. Spinach grown at 75°F was damaged 4 times more severely than when grown at approximately 55°F. Romaine lettuce grown under the same conditions showed 30% more damage at the higher temperature than it did at the lower. Endive responded similarly. The leaves of romaine lettuce were made progressively more resistant to damage by their periodic prior exposure to air temperatures of approximately 55°F, as demonstrated in Table III.

The application of nitrogen to soil in 6-in. pots at the rate of 45 lb./acre increased the amount of injury to spinach leaves 40% and romaine lettuce 80% compared to plants not receiving nitrogen additions. Barley grown in soil without nitrogen addition yielded an injury index of 0; whereas with added nitrogen the index was increased to 1.2. Oats without nitrogen additions were not injured, but upon adding nitrogen an injury index of 2.5 was secured. This shows a predisposition towards injury by nitrogen addition as well as a greater susceptibility to damage on the part of oats than barley.

In addition to the injury to saleable parts of agricultural commodities it has been discovered that real damage may occur because the growth of some plants may be materially retarded without any visible symptoms of injury. It is impossible to recognize this effect in the field since all of the plants in a given area may be subjected to sublethal dosages of the toxicant leaving no healthy plants for comparison. Growth suppression has

[8] Middleton, J. T., Kendrick, J. B., Jr., and Darley, E. F., "Airborne Oxidants as Plant-Damaging Agents," *Proc. Third Natl. Air Pollution Symposium* (1955).

TABLE 1

Susceptibility of Bean Varieties to a 7-hr. Exposure of 0.28 ppm. of Oxidant from Ozonated Hydrocarbon.

Variety	Extent of Injury
Bountiful	2.8
Kentucky Wonder	4.2
Mexican Red	9.0
Pink	9.4
Pinto	8.8
Red Kidney	2.0
Small White	8.9

TABLE II

Effect of Age in Number of Days Since Plants Emerged from the Soil of Pinto Bean Primary Leaves Upon Injury by Ozonated Hydrocarbon.

Days	Extent of Injury
3	1.2
4	2.6
5	3.5
6	5.2
10	7.7
18	9.4
26	10.0
34	10.0

TABLE III

Romaine Lettuce Grown at 75°F Air Temperature and Predisposed to Reduced Injury from Oxidized Hydrocarbon by Exposure to 55°F.

Days exposed prior to fumigation	Extent of Injury
0	8.9
1	8.8
2	8.6
3	8.5
4	7.3
6	6.7
7	6.1
8	5.1
9	3.8
LSD at 19:1	0.9
LSD at 99:1	1.3

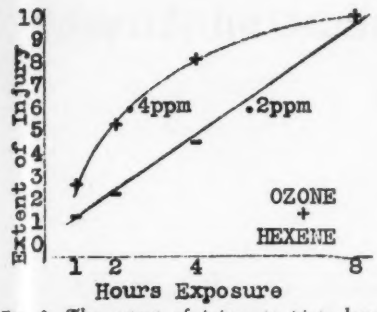

Fig. 3. The extent of injury to pinto bean leaves resulting from exposure for varying periods of time to 2 levels of ozonated hexene.

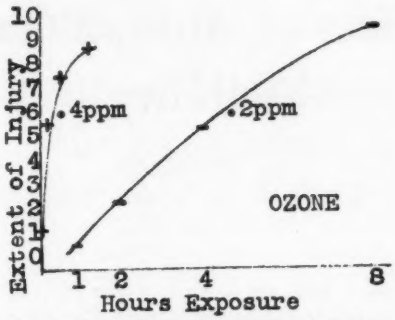

Fig. 4. The extent of injury to pinto bean leaves resulting from exposure for varying periods of time to 2 levels of ozone only.

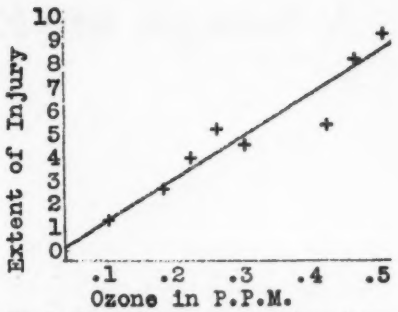

Fig. 5. Extent of injury to pinto bean leaves resulting from a 4-hr. exposure to several levels of ozone only.

been experimentally induced in alfalfa, endive, lettuce, oat, sugar beet, and tomato. These observations corroborate the earlier findings of Koritz and Went[5]. Seedling Mexican avocado trees exposed for 3 mo. to ozonated gasoline, however, did not show any growth retardation. The possible effects of exposure to the reaction products of oxidized hydrocarbons and the retardation of growth in citrus and its relationship to production of small fruit size in oranges is currently under study.

Bean leaves exposed to oxidized hydrocarbons for too short a duration to cause visible damage have been shown by Wedding *et al.*[13] to result in a decrease of the permeability of the plant cells to the inward and outward movement of water and radioactive phosphorus. Longer exposures which result in the appearance of visible leaf injury reverse this effect bringing about a progressive increase of the permeability of the cells to both water and radioactive phosphorus. These facts may be of importance in explaining both growth suppression effects of air pollution, which may be a result of the decreased ability of the plant cells to take up water and nutrients, and the necrosis of the leaves exposed to heavy doses which may destroy the ability of the cells to retain water against an outward concentration gradient which results in the drying out and death of cells and development of the silver and bronze symptoms. The effect of ozonated olefins and ozone upon photosynthesis, respiration and enzyme systems is under study by these investigators in conjunction with G. W. Todd of the Department of Plant Biochemistry, University of California, Riverside. The results of their research should provide a means of understanding the nature of the retardation effect of oxidized hydrocarbons upon plants.

With this knowledge of the response of plants to polluted air containing oxidants the specific response of pinto bean leaves to natural and artificially contaminated air becomes one of the most useful tools in assessing the effects of air pollution, the types of pollutants present, and their geographic distribution[6]. The pinto bean response to the oxidation products of gasoline and ozone is the development of a silver and bronze pattern on the lower leaf surface. The upper leaf surface becomes bleached in the presence of ozone alone. The extent of injury depends upon the length of fumigation and the concentration of the toxicant. The injury to leaves of pinto bean shows a linear increase with increasing hours of exposure for a given concentration, as shown in Fig. 3. The extent of injury with reacted hexene is greater at 0.4 ppm. than at 0.2 ppm. during the first 4 hr. of exposure, but this difference is not as apparent after 8 hr.

The extent of injury to leaves exposed to 0.2 ppm. of ozone only is approximately the same as that for leaves exposed to a mixture of ozone and hexene yielding 0.2 ppm. oxidant (compare Fig. 3 with 4). Increasing the ozone concentration from 0.2 ppm to 0.4 ppm. markedly increased the extent of injury to exposed leaves as shown in Fig. 4. A linear relationship between the extent of injury and the concentration of ozone is shown in Fig. 5 in which plants were exposed to varying concentrations of ozone for a single 4-hr. period in successive experiments.

The atmosphere in Los Angeles and San Francisco allegedly has high concentrations of ozone. Yet typical crop damage there is that reproduced only by ozonated olefins and not by ozone alone. Ozone damage to crops in these two areas is of rare occurrence and of no economic concern. A plant damage survey conducted in cooperation with the Air Pollution Foundation in the summer of 1954, using pinto bean as a test plant, corroborates these observations since ozone damage to these beans was found on only 2 occasions and typical crop damage attributable to ozonated olefins was rather consistently found during periods of pollution[9]. Pinto beans are more seriously damaged by ozone than they are by reaction products of ozone and olefins. The extent of damage to pinto bean leaves to 0.4 ppm. ozonated olefins for a 4-hr. exposure is approximately the same as exposure of similar plants to 0.4 ppm. of ozone for 20 min. This plant response indicates that it is essential that a biological system, perhaps the pinto bean, be used as an adjunct for the proper interpretation of oxidant levels since potassium iodide and phenolphthalin do not readily discriminate between oxidants of different phytotoxic potentials.

Topical application of aqueous suspensions of a number of bisdithiocarbamates was shown by Middleton *et al.*[7] to prevent injury to leaf tissue resulting from exposure to natural air pollution as well as to oxidized hydrocarbons. Kendrick *et al.*[4] reported dusts of these

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A Note on the Effect of Aircraft Exhaust on Airport Visibility*

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On December 4, 1954, the forecast for a mission from Limestone to Goose Bay did not verify completely because the terminal conditions at Goose Bay were below landing minimums. Three flights of aircraft were involved. The first flight requested and received permission to make a jet penetration and landed without GCA (Ground Controlled Approach). When the second flight arrived, the weather had deteriorated. All aircraft were brought in by GCA. It was reported that the F-86's, while milling around, had "seeded" the area and reduced ceiling and visibility over the field. The third flight had more trouble but landed after some confusion and several GCA passes. A check with technical representatives provided information that F-86 engines are very inefficient at low altitudes and have been known to "seed" areas at, near, or below freezing temperatures. It was requested that a study be made of the alleged seeding phenomenon, and that information be secured enabling meteorologists to forecast the responsible weather conditions.

A total of 17 F-86 aircraft were involved in this incident, the first flight reaching the field shortly after 1600 GMT. Extracts from the hourly sequences for the weather during the critical period are shown in Table I. It is seen that the weather conditions deteriorated as the aircraft made their passes and landings and then again improved. The possibility that the deterioration of the weather was a result of natural causes which by chance coincided with the arrival of the aircraft cannot be eliminated entirely. However, the fact that the synoptic situation remained unchanged and that the weather again improved after the aircraft landings certainly indicates the probability of a causal relationship between the landings and the weather.

Influence of Aircraft on Environment

An investigation was made into the several ways in which aircraft might affect visibility and ceiling. It is known that the water vapor produced during combustion of hydrocarbon fuels can raise the relative humidity of the environment provided the temperature is below a certain critical value. Condensation trails and ice fogs result from such combustion[1, 2, 3]. However, at sea level this critical temperature is —29°C or less, depending on the ambient relative humidity; at higher altitudes the value is even lower. The surface temperature at Goose Bay at the time of reduced visibility was 10°F (— 12°C). The 950 mb temperatures from the 1500Z and 2200Z soundings were —14.8 and —14.3°C respectively. Since at temperatures higher than the critical, combustion actually reduces the relative humidity of the air, it can be stated with confidence that the decreased weather conditions were not a result of addition of moisture to the air by the combustion process. A plot of the December 4/0900 and December 5/0300 soundings for Goose Bay (the only ones available in the Daily Upper Air Bulletin) indicated that the lowest possible level of contrail formation was around 17,000 feet. (Fig. 1).

The other reasonable possibility involved the output of smoke and condensation nuclei in the exhaust gases. It is known that jet aircraft are very inefficient at low altitudes, and hence put out a large amount of exhaust gases/unit length of travel. One frequently observes a trail of heavy black smoke behind aircraft during take off, indicating incomplete combustion. In a study on atmospheric pollution in the Los Angeles area, Haagen-Smit[4] showed that incomplete combustion from automobiles releases large quantities of hydrocarbons into the air. Combustion also produces nitrous oxides. He found that the oxidation of the hydrocarbon particles by nitrous oxide gives a haze formation which can blur objects within a short distance. Magill and Benoliel[5] also reported on the deleterious effect of combustion pro-

(Continued on page 50)

* Reprinted from the *Bulletin of the American Meteorological Society*, 37, 19-21 (1956).

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TABLE I
Hourly sequence for Goose Bay, Labrador, December 4, 1954.

Type	Time G.M.T.	Sky condition	Vsby miles	Wea.	T °F	Td °F	RH %	Wind
R	1520	E45⊕	9	S—	9	4	80	W3
R	1620	E40⊕	8	S—	10	6	84	W3
S2	1635	P10⊕	1	S—				C
R/S3	1720	—XE25⊕	2½	S—	10	7	88	C
S4	1725	P18X	¾	S—				C
S5	1735	—XB25⊕	1	S—				C
S6	1750	E30⊕	6	S—				C
R	1820	25⊕A50⊕	7	S—	12	8	86	C
S7	1850	30⊕E50⊕	15	S—				C
R	1920	30⊕E50⊕	20	S—	11	8	89	C

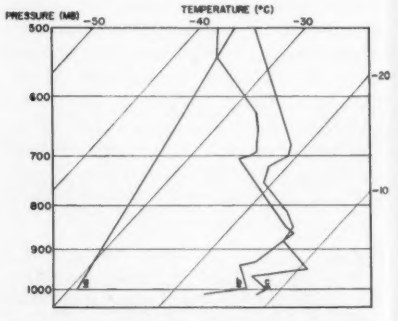

Fig. 1. Radiosonde observations at Goose Bay, Labrador, December 1954. Curves b and c represent soundings for 4/0900 and 5/0300 GMT, respectively. Curve a shows maximum ambient temperatures for contrail formation as a function of height.

Atmospheric Diffusion Formulae and Practical Pollution Problems† *

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The literature of air pollution needs a brief, summary paper reviewing the practical application of atmospheric diffusion formulae in terms of typical industrial plant problems. Most papers, and even handbook sections in this general category, deal with selected aspects of the problem or present data from a limited field survey. Although it is possible to draw useful conclusions from the varied source material, apparent inconsistencies are often encountered. The purpose of this paper is to suggest a general plan of approach that may dispel some of the existing confusion.

Specification of the Problem

The most obvious starting point in any air pollution problem is one often neglected; the *source* parameters and possible pollutant *effects* must be established as fully and accurately as possible at the outset. All further work is dependent on these basic data. The essential information for a typical plant is contained in the following list:

1. Source Parameters. Planned or existing values and possible variations in:
   a. Number and configuration of pollutant sources.
   b. Height of source(s).
   c. Pollutant emission rate.
   d. Vertical speed of emission.
   e. Density of total effluent.
   f. Volume of total effluent.
   g. Nature of pollutant(s).
   h. Possible physical or chemical changes in pollutant during and after emission.
   i. Plant operation—level of operation and schedule.
   j. Pollution from other local sources.
2. Pollutant Effects.
   a. Survey of the probable and possible effects of pollutant associated with various time periods and concentrations.
   b. Estimation of the relative importance of effects covered in a. above.
   c. Possibility of other sources producing additive or synergistic effects.

Such a listing may appear trivial, but it is remarkable how often one or more of these vital factors is neglected or incorrectly specified. An example, in which proper recognition of the major effect of a pollutant conditions the subsequent analysis, illustrates the point. Consider an effluent whose effect is primarily related to gradual accumulation of the material by the human body, such as beryllium. An analysis of diffusion from a typical industrial beryllium source should be directed only toward establishing probable figures for one case, namely the maximum long-term mean value and the area in which it will be found. Detailed analysis of transitory concentration patterns is largely of academic interest. Similarly, effort need not be devoted to spot concentration measurements since only long-term data are meaningful.

Effluent Rise and Local Aerodynamics

Following establishment of the source parameters and pollutant effects, the behavior of effluent close to the plant must be analysed. This implies joint consideration of 2 rather different subjects, (1) the rise of stack effluent owing to jet and buoyancy forces, and (2) the production of localized eddies by nearby structures and topographic features.

It is usually best to begin with a set of calculations of effective stack height in order to obtain some idea of the height increment likely to be associated with the effluent source(s). This poses the question of selecting the proper formula for the computations, and the following considerations should govern the choice:

1. If there is relatively little density effect (*i.e.* effluent temperature $\leq$ 10-15°C above air temperature) there is little choice among a number of formulae. For example, the equations of Bosanquet[3], Callaghan[4], and McElroy[11], will give fairly similar estimates for jet effects.
2. Where the effluent is relatively hot and the volume of emission is substantial ($\leq$ 100,000 cfm.), it is most important to evaluate the buoyancy effect. It is the author's conviction that the best estimate is achieved by the use of the Bosanquet, Carey and Halton equation[3].
3. It is important to keep in mind the following points concerning all such equations:
   a. They are empirical, generally based on wind tunnel studies. Field data suitable for evaluation are sparse, since all the necessary data are seldom obtained.
   b. At relatively high wind speed-stack speed ratios most of the formulae correctly predict small jet and density effects. At lower ratios many of the formulae become too conservative. This is the basis for recommendation of the Bosanquet approach.
   c. With very light winds, the problem degenerates into guesswork.
   d. Winds used for such evaluations should be representative of stack-height, not ground-level.

The estimates of *effective stack height* can now be considered in relation to local aerodynamics, with the realization that a calculated effluent rise will be unreliable if the plume is caught in an adverse standing eddy that will force it close to the ground.

General rules concerning local aerodynamics are hard to formulate. No theoretical treatment is available on which to base a decision, and no 2 cases are identical. It is reasonably safe to conclude that in level country an isolated plant having *effective stack heights* of at least 2.5 times the building height in all probability winds will not be subject to adverse aerodynamics. It is likewise sensible to expect a plant utilizing roof-

† Research carried out under the auspices of the U. S. Atomic Energy Commission.

* Presented at the 48th Annual Meeting of the Air Pollution Control Association at Detroit, Michigan, May 23-26, 1955.

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level stacks, or stacks low in comparison to other nearby structures, to have frequent aerodynamic *downwash*. Only wind tunnel tests of the type conducted by Sherlock[13] can give positive results.

The best guide in deciding whether to resort to wind tunnel tests is a search of the literature and experimental data for results obtained at plants similar to that proposed. If wind tunnel tests are undertaken, it is important to recognize that they can be relied upon to solve only true aerodynamic problems, *not* atmospheric diffusion problems. Assuming that unfavorable aerodynamic effects are either initially absent or eliminated by design changes, the necessary parameters are now available for use in predicting the diffusion, with the effective stack heights serving as true stack heights in subsequent calculations.

Meteorological Dispersion

The foregoing sections have paved the way for analysis of the role of natural air turbulence in further dispersion of effluent. It should be stressed that this entire portion of the discussion applies to ground-level concentrations of gaseous or small particulate ($\leq 10\ \mu$) effluent. The problem of larger particulates is a specialized case. At the present state of our knowledge, estimates of the dispersion resulting from meteorological processes are reliable in a substantial number of circumstances. However, the applicability of the formulae may be sharply limited by many factors. It is difficult to separate these factors for individual consideration since they are often interdependent, but some attempt must be made to obtain a picture of the problems:

Fundamental Dispersion Patterns

It is most important to reaffirm at the outset that 2 basic conditions of atmospheric stability have been recognized, the so-called *lapse* condition in which temperature decreases with height and the inversion condition in which an increase is found. There are many variations of degree and character of these stability conditions. However, variations are secondary to the important distinction that, while the dispersion formulae of Sutton[19], and Bosanquet and Pearson[2], may be applied successfully to lapse conditions, they are not suitable for inversions[16]. The reason for this is relatively straightforward; the treatment of both Sutton, and Bosanquet and Pearson assume vertical as well as horizontal diffusion, whereas in nature the vertical dispersion is practically nonexistent during inversions. For the most part, inversions are nocturnal and the lapse conditions are found during the daylight hours. For the latter, the Sutton point-source diffusion formulae give values whose general accuracy is fairly well known. It has been found that, even for different effluents [5,16] the predictions will be somewhat pessimistic when used for estimates of mean concentrations of 1 or more hr., but the distances and order of magnitude of predicted concentrations are correct. The use of values of the parameters other than those given by Sutton is not generally recommended. Despite the fact that many researchers have arrived at different values for certain locations and sampling periods, very few of them are based on data of sufficient reliability to warrant making any change. The Brookhaven values given by Smith and Singer[18], are reliable for that site, but their applicability elsewhere is questionable. The Bosanquet and Pearson formulae may also be used for daytime predictions[7], but with somewhat less flexibility. It should be remembered that these treatments pertain to point source formulae, giving infinite concentration values at zero distance. Estimation of the distance at which values become realistic has been given by Lowry[10]. The distinction between *average* and *typical* conditions is also important, as has been stressed by Singer[15].

If the concentrations to be found during temperature inversions cannot be predicted with the usual diffusion equations, an alternative procedure is needed. Fortunately, it may not be necessary to complete such an evaluation in cases wherein the effective stack height computations show that effluent will clear all local terrain and high structures. If it is necessary to compute inversion plume concentrations, this can be accomplished by treating the plume as a pie-shaped wedge, initially having a volume and concentration commensurate with the stack parameters, and widening downwind at a horizontal angle of 3·5° while maintaining constant vertical thickness. This technique, developed by the author and described by Hewson[8], can be extended for the computation of fumigation conditions. While the method is admittedly an over-simplification, in the absence of good data on which to base a more sophisticated treatment, the approach is probably as good as any available. Barad[1] presents a much more thorough consideration of inversion effluent dispersion, but all treatments await data for evaluation.

Terrain Features

Like plant aerodynamics, the influences of terrain can hardly be covered in a survey discussion, and formulae are not available with which to predict them. Even so, it is worthwhile to indicate some of the more important effects that terrain may have upon the reliability of diffusion formulae. The effect most difficult to estimate is the influence of surface roughness on the parameters used in the diffusion equations. Very few data of sufficient quality and quantity to assist in evaluating these differences can be found. The author's best estimate at present is that the diffusion parameters appropriate for tall stack pollution problems are closely related to relatively long-period convective eddies[18], and as such are not strongly related to minor surface variations.

Terrain may produce wind patterns that tend to be repeated very frequently with the result that there is a strong tendency for certain areas to receive a large proportion of the total effluent concentrations. Long, parallel ridges and valleys are most effective in producing such results.

Aerodynamic *downwash* may be associated with sharp topographic features as well as man-made structures, and if this is true, the idealized diffusion formulae will not be reliable. Delineation of the proper role of wind tunnels in assessing the aerodynamics of topography and in substituting for meteorological analysis is one of the more controversial issues in the field of air pollution today[13, 17].

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All agree that tunnels apply to building-scale phenomena, and most agree that they do not represent a scale of tens of miles adequately. The most important region in between the two is in dispute. It seems reasonable to adopt a pessimistic view of such tunnel results until firm comparisons with actual field experience can be shown. Therefore, field tests with appropriate tracer materials become the reliable means of solution.

Time Factors

One of the neglected aspects of diffusion formula applications is the relationship of mean values to time. Admittedly, most literature on the subject does not stress the importance of time, although the point is emphasized occasionally. Field tests of various types are gradually revealing that one cannot dispose of the problem by using undefined terms such as *average* and *instantaneous*. Any set of calculations of effluent concentrations applies to a certain time period but not necessarily to others. For example, the values given by Sutton[19] seem to apply reasonably well to periods of about 3 min., but predict concentrations that are too high for hourly average values. In general, average concentrations decrease with increasing time periods at least up to 1 hr. It has been found that for Brookhaven oil-fog data, the general relation between peak (10 sec.), eddy (period when smoke was continuously present) and test average (30 min. to 1 hr.) is about 20: 5: 1. Gosline[6], reports ratios of the same order. Such variations must be considered in relation to each individual problem.

Time may also be important in quite a different way if periodicity is found in ground-level effluent concentrations. The current meteorological program at Brookhaven includes an investigation of the spectra of oil-fog concentrations[18] and the initial results show such periodicity for typical daytime conditions. It would appear that fluctuations of 8-10 min. periods are most important in the variation of ground-level concentrations from this 355 ft. test stack. Further data may be expected to apply particularly to odor problems, in which the magnitude and time periods of fluctuations in pollutant concentration can be extremely important.

Space Factors

Variations in ground-level concentrations about the long-term mean values become smaller with increasing distance. For example, the more complete Brookhaven oil-fog data reported upon by Lowry, Mazzarella, and Smith[9], show that the ratio of peak (10 sec.) values to average values for the sampling periods (.5 to 1.5 hr.) decreases with distance. The mean ratio for cases up to 2 km. from the source was 20, whereas that for measuring points further away was only 6. These cases were selected for the typical daytime B_1 gustiness class[14] so that the measurements are comparable. Vertical variations are, of course, very important, especially close to the source where the limits of the effluent plume are sharply defined. Although it is a fairly obvious conclusion, it is also worth noting that the point source approximation tends to become better with increasing distance, in that local aerodynamics, errors in effective stack height estimates and complications arising from multiple source emissions dwindle in importance.

The significance of both time and position is strikingly illustrated by an actual case in which a complaint was made that effluent from an industrial plant was being measured at concentrations of 25-30 ppm. on neighboring property, while the test measurements made by the plant personnel seldom exceeded 2-3 ppm. Both measurements were correct: the high values were small-volume air samples obtained on an open elevated structure at night when the concentrated effluent plume was passing through the framework; the lower values were longer-period measurements made at ground-level during typical daytime situations.

Multiple Sources

So far we have dealt with the problem of a single stack that can be represented by a point source approximation. Frequently, the emission from a plant does not (or need not) come from a single source. The difficulty then lies in estimating the combined effect. If the stacks are widely separated, the problem is simple, for the plume shapes associated with various meteorological conditions can be described by isolines of concentration at ground-level and the results added directly wherever and whenever the plumes overlap. The problem is very complex when several stacks are located close together (*i.e.*, 50-150 ft. apart). With such a configuration it is very probable that the joining of the plumes after initial emission has an effect similar to that which would be produced by a volume larger than that from any of the individual stacks. This would give an effective stack height greater than predicted for the single sources. One would expect this effect to be more pronounced with winds parallel rather than at right angles to a line of stacks. So far, no quantitative data have been published on this problem, and simple addition of the overlapping concentrations is probably the safest procedure.

The author has had the opportunity to make a comparison of calculated and field concentrations for 1 set of 20 identical stacks. Both crosswind and parallel wind concentration predictions agreed very well with the actual measurements, but the data were by no means sufficient to constitute a reliable study.

Particulate Effluents

All of the foregoing discussion applies to concentrations of gaseous effluents or particulates of $\leq 10\ \mu$ in diam. It has no certain relation to the deposition of particulate material, except to fix limiting theoretical values. Estimates of the fallout of large ($> 20\ \mu$) particles can be approximated by the Bosanquet, Carey and Halton[3] technique with some likelihood that the results will be correct to an order of magnitude, but, as pointed out by Ranz and Johnstone[12], other forces may become at least as important as gravity in controlling the deposition of particles as small as $1\ \mu$. Modern air cleaning equipment, fortunately or unfortunately, removes the larger, more predictable particles and leaves only the difficult ones.

Conclusions

A systematic evaluation of a typical industrial air pollution problem does not presuppose the necessity of any particular method of analysis or testing. It should begin with careful evaluation of source parameters and pollutant effects to determine precisely what estimates will be valuable.

Behavior of the effluent near the source involves the joint consideration of 2 factors, aerodynamics and jet-density effects. The latter can be calculated, but the former is a wind tunnel problem.

Calculation of turbulent diffusion of gaseous or small particulate effluent in the natural atmosphere is undertaken subsequent to the evaluation of local effects. Results of usable accuracy can

(Continued on page 49)

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Effects of Topography on Winds and Diffusion Conditions at the National Reactor Testing Station*

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The topographic effects on the winds over East Idaho are of interest to meteorologists at the National Reactor Testing Station (NRTS) because of their influence on the dispersion of stack effluents there. One might suppose that topographic effects would be a minimum out in the middle of the 60-mile wide Snake River Plain, but actually they are more important than the large scale pressure gradient.

A relief map of Eastern Idaho is shown in the Fig. 1. The Continental Divide borders the plain to the north, and the valley is oriented northeast-southwest. The expanse of the valley floor is so great compared with the heights of the mountains on either side that cross-valley winds are not prominent over the middle of the valley. Due to channeling of the westerlies and air drainage, there is an almost continuous flow of air out of the smaller valleys opening into the plain from the northwest. This flow does not reach far out, but rapidly turns to conform to the flow existing over the plain. The wind data, which will be presented later, were taken at the stations marked WBO and WXA. Idaho Falls is about 30 miles east of the NRTS; Pocatello is 40 miles southeast; and Dubois is 30 miles northeast.

Topographic cross-sections along the dash lines XX' and YY' are shown in the Fig. 2. The outstanding features are the general slope of the plain upward to the northeast and the channel formed by the mountains to the east and west of the Snake River Plain.

The most important topographic effects in this region are: mountain-valley breeze, which tends to give southwest (valley) winds over the NRTS in the daytime and northeast (mountain) winds at night; channeling, which causes surface winds to curve in following the contour of the valley; barrier effect, which gives descending air currents in the lee of the mountains just west of the NRTS; basin effect, which causes stagnation of the air during certain conditions; standing eddy over the north end of the plain; and zones of wind shear that migrate across the plain.

Mountain-Valley Breezes

The mountain-valley breezes are quite pronounced, especially during the warmer months. They often prevail against strongly opposing pressure gradients (as seen on synoptic weather charts). The mechanism of the interaction of slope winds with mountain-valley winds, described in great detail by Wagner[1] and illustrated schematically by Defant[2] is verified for this region. Fig. 3. (at the top) shows the model valley, where so-called slope winds occur on the steeper slopes of the sides of mountains, and so-called mountain-valley winds occur on the gentler slopes of valley floors. Due to the presence of the Continental Divide to the north of the valley, the schematic plan for this region is more like the lower sketch.

Fig. 4. shows hourly frequencies of winds from 4 quadrants in summer at the WBO station. The lag in time of direction change (past sunrise and sunset) typical of mountain-valley regimes is evident, as is the typical cyclic shift in wind direction in the course of a day where upslope winds begin just prior to valley winds, and downslope winds begin just prior to mountain winds.

Channeling

The importance of the channeling of winds through the valley is the control exerted on the direction of the winds. This control is such that sites on the plain well away from the mountains experience up-valley and down-valley winds almost exclusively. Also, since the valley is curved (it is oriented east-west at Boise and about north-south at its northern extremity), the streamlines of the winds are curved, at least in the lower few hundred feet. The effect is noticeable even within the NRTS boundary,

* Presented at the 48th Annual Meeting of the Air Pollution Control Association at Detroit, Michigan, May 23-26, 1955.

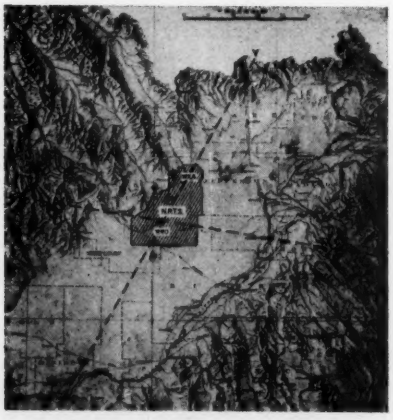

Fig. 1. Snake River Plain of Eastern Idaho.

(1) Wagner, A., Theorie und Beobachtungen der periodischen Gebirgswinde. *Bietr. Geophys.*, 52, 408-449 (1938).

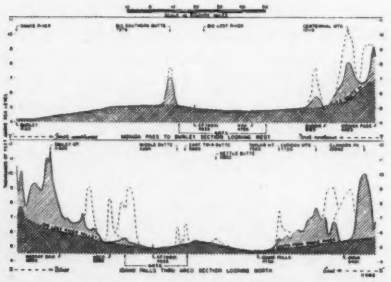

Fig. 2. Topographic cross-sections north-south and east-west across Eastern Idaho, taken along the lines XX' and YY' of Fig 1. Dash lines show important contours within about 10 miles of the sections.

(2) Defant, F., Zur Theorie der Hangwinde, nebst Bemerkungen zur Theorie der Berg-und Talwinde. *Arch. Meteor. Geophys Biokl.*, 1 (A), 421-450 (1949).

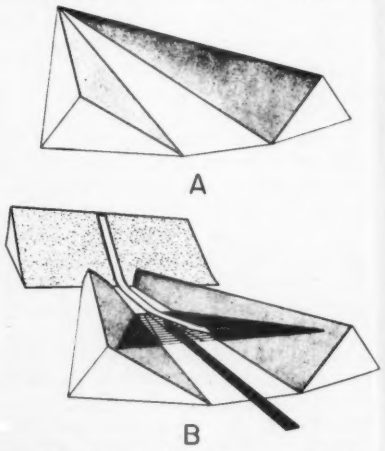

Fig. 3. Schematic plan for an ideal valley after Defant (A) and schematic plan of Snake River Valley, showing how miniature front is formed out of conflict between valley wind and katabatic wind down the slope of the Continental Divide (B).

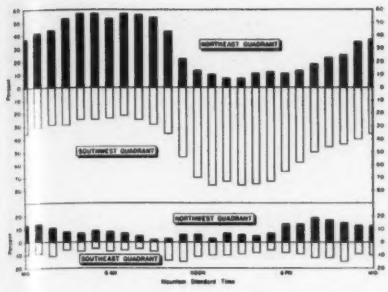

Fig. 4. Hourly frequencies of winds from 4 quandrants in summer, NRTS, Idaho.

as can be seen by comparing annual wind roses for the WBO and WXA stations, Fig. 5. These stations are only 24 miles apart on an open plain, and normally it would be assumed that a wind rose for one station would be representative for the other. A very serious error could be made in site planning (stack and building arrangement) if differences such as those shown here are not taken into account.

Descending Currents

Winds aloft are predominantly westerly over the region, so that the NRTS lies on the lee side of the mountain barrier to the west. The subsiding of air over the NRTS region is evident from its dryness relative to the surrounding country. For example, precipitation over the NRTS averages about half as much as at Pocatello, Idaho Falls and Dubois. Often clear skies are observed over the NRTS when it is cloudy elsewhere over East Idaho. In winter, the snowline usually can be seen between the NRTS and Idaho Falls.

The effects of the descending currents on stack effluent behavior are secondary ones, since the currents do not descend all the way to the ground. The absence of cloudiness has a profound effect on terrestial heating and cooling, which, of course, affects the diffusive properties of the air. The infrequency of precipitation, for all practical purposes, makes consideration of the washing down of stack wastes unnecessary.

Basin Effects

The Snake River Plain is sufficiently open that it is not often subject to the long stagnant periods characteristic of more confined areas, but these conditions do occur occasionally in winter with snow cover and an anticyclone present. Due to drainage of cold air from surrounding mountains, the plain becomes covered with a dense mass which resists movement even when the circulation aloft changes. In this static condition the air in the valley has a stable stratification, resulting in a very poor diffusion condition.

Large Eddy

The topographically-produced eddy that occurs over the north end of the plain in winter is favored by strong south to southwest winds, such as those produced by an approaching low pressure system. The plane of circulation of the eddy is vertical, as shown by a shallow northerly surface wind topped by southerly winds aloft. The eddy has been known to persist for more than 24 hr. At the south edge of the eddy there is a line of shearing surface winds, and this shear zone has been detected within

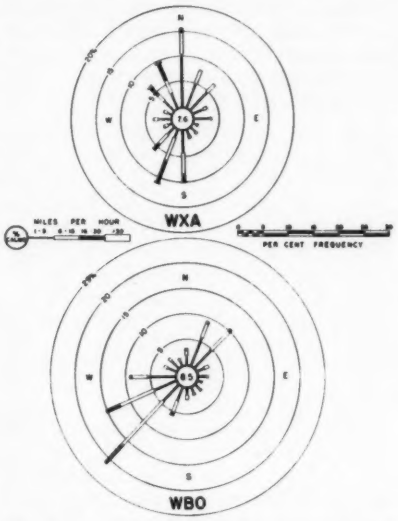

Fig. 5. Annual wind roses for stations WXA and WBO showing effect of curvature of streamlines.

the network of weather stations on the NRTS. When the eddy is smaller, the shear zone occurs to the north of the NRTS, and often the winds at Dubois (30 miles northeast of the NRTS) are northerly when south winds prevail over the rest of the plain. From a study of the migrations of the shear zone, it appears that it occurs further south (and consequently the eddy is larger) when the wind flow over Idaho is southerly rather than southwesterly. It has been seen to recede northward as the upper winds veered from south to west.

An example of one of the most extensive eddies discovered to date is shown in Fig. 6, which is a reproduction of a portion of the 2330 MST surface synoptic chart for January 2, 1954. Note that the northerly surface wind, which is in direct opposition to the flow indicated by the pressure contours, covers the entire Snake River Plain. The upper wind followed the pressure contours, as seen by the arrow (pointing northward over NRTS) which represents a SSE wind of 29 mph. measured about 1700 ft. above the plain at a station on top of an isolated mountain peak. It cannot be said whether the northward bulge of the pressure contours along the Continental Divide is characteristic of such an extensive eddy, but smaller eddies have been observed when no such isobar configuration existed.

Zones of Wind Shear

A more frequent, and thus more important, source of wind shear zones over this region is due to a conflict between a wind down the slope of the Continental Divide and the valley wind (Fig. 3). This phenomenon was the subject of a paper read for the author at the 131st meeting of the American Meteorological Society[3]. Since the steeper slope at the upper end of the valley faces south, its diurnal range of temperature is large, and the slope winds there are frequent and pronounced. It is obvious that there must be a conflict between the valley wind and the downslope wind at night due to the lag in the change from up-valley to down-valley flow. There must be also a divergence at the north end of the valley (between upslope and mountain wind) in the morning when the upslope flow begins, continuing until the valley wind takes over in the forenoon. Both situations have been observed, although the divergence takes place more

[3] Wilkins, E. M., A Discontinuity Surface Produced by Topographic Winds over the Upper Snake River Plain, Idaho. Paper presented at 131st Meeting of American Meteorological Society, Columbus, Ohio, September, 1954,

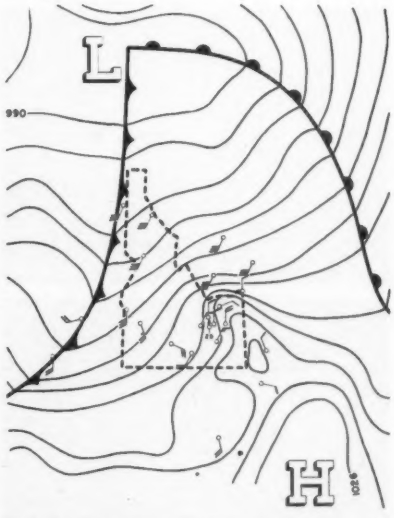

Fig. 6. Portion of surface synoptic weather chart for 2330 MST Jan. 2, 1954, showing surface winds over Eastern Idaho flowing opposite to the direction indicated by the pressure gradient.

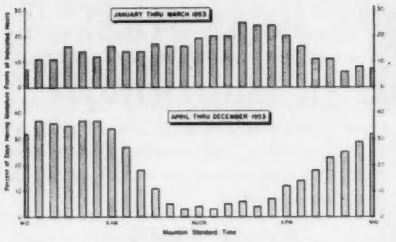

Fig. 7. Diurnal frequency of occurrence of wind shear zones on the NRTS as detected between 2 recording stations.

Fig. 8. Effect of shear zone on a smoke plume from a 250-ft. stack, NRTS, 0722 MST, April 11, 1952

often beyond the north boundary of the NRTS.

The shear zone caused by converging downslope and valley wind was first noted as an excess in the frequency of the northerly winds at the WXA station as compared with the WBO station. It was later discovered that the conflict of winds noted at the surface was associated with a situation where layers of air at the surface and aloft move in opposite directions. The boundary between the layers has a slope comparable to a front, and, indeed this miniature counterpart of an air mass front often exhibits temperature differences across the boundary in excess of 10°F, in contrast to the shear zone associated with the eddy. Although a sizeable temperature contrast is not a necessary condition for the front to exist, the shear zone always slopes upward in the direction of the cooler air.

This shear zone, or *miniature front*, occurs with fair weather, and since it is mostly a nocturnal phenomenon, a surface temperature inversion is always present (again in contrast to the shear zone produced by the eddy). Also in contrast is the fact that the occurrence of the miniature front on the NRTS is independent of the direction of the pressure gradient, as long as the upper winds are not strong.

The frequency of occurrence of these miniature fronts by time of day is shown in Fig. 7. Note that the greatest frequency is near the time of maximum temperature January through March. During these months there was a snow cover on the Divide, but not in the valley, so that the downslope effect was present day and night. This downslope wind, of course, is more likely to be opposed by the valley wind during maximum solar heating.

The effect of the shear zone on an effluent plume from a 250-ft. stack on the NRTS is shown in Fig. 8. The lower part of the plume is traveling northward and the upper part southward. The picture was made early in the morning in April 1952. The shearing of the plume was observed for about 30 min. until the southerly flow deepened to such an extent that it engulfed the entire plume. There was no indication of turbulence in the shear zone at any time; however, the 2 layers of air were moving at a speed of only about 6 mph. with respect to each other.

Fig. 9 shows a sequence of pictures of a debris cloud from the explosion of an ammunition igloo on the NRTS (which was then the Idaho Navy Proving Ground) on August 29, 1945. Special observations taken for the experiment show northeast winds from the ground to 900 ft., and southwest winds above. A *miniature front* likely was present, and it appears to have sloped upward to the north.

Conclusion

The best knowledge of the effect of the wind shear phenomena on effluent dispersal will come from an understanding of the circulation pattern associated with them, and this is being studied by means of smoke observations, wind and temperature soundings and by tower instrumentation. It is not expected that

(Continued on page 51)

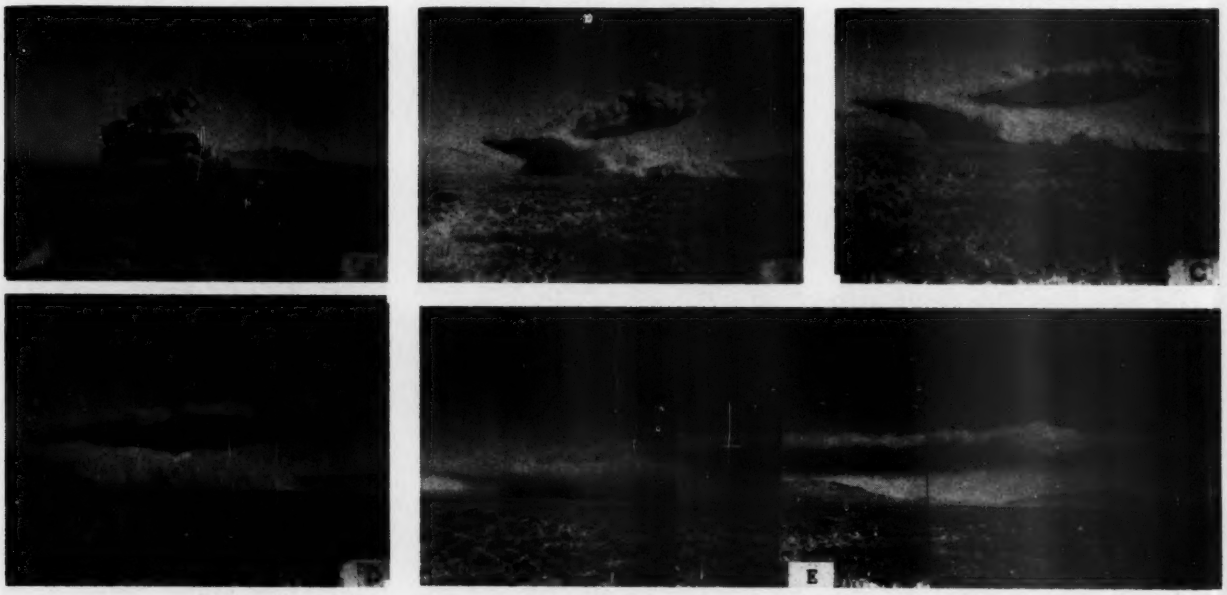

Fig. 9. Effect of shear zone on a cloud of smoke from an experimental explosion, Aug. 29, 1945.

Removal of Halogens, Carbon Dioxide, and Aerosols from Air in a Spray Tower*

R. C. LIIMATAINEN and W. J. MECHAM
Argonne National Laboratory
Lemont, Ill.

This article describes tests made on a multiple nozzle spray tower designed to remove highly reactive and toxic halogen compounds, such as bromine pentafluoride, bromine trifluoride, etc., that might be carried in the exhaust air from a laboratory area using these materials. A previous report[1] from this laboratory reviewed the biological tolerances and some earlier absorption work reported in the literature. This report described experiments on the absorption of these materials in a limestone bed and in a single nozzle spray tower using caustic solutions. The present work is an extension of the spray tower studies to larger scale operation and to some additional airborne materials, namely, iodine, carbon dioxide, and aerosols.

In the work cited above, the limestone bed was relatively poor in both removal efficiency and capacity for halogen compounds other than hydrogen fluoride, and larger scale bed designs involved excessive total weight and high pressure drop for the ventilation installation proposed. The spray tower, however, proved quite generally attractive. Some typical results are shown in Table I, for later comparison with results of the larger unit. This 5-in. diam. single stage spray tower was also used to dispose of 70 lb. of mixed interhalogen wastes. These highly reactive materials were safely and effectively hydrolyzed with inlet interhalogen concentrations as high as 80 mol % in air, and mass rates as high as 3 lb./hr. A spray tower rather than a packed tower was chosen primarily because of the former's lower pressure drop, a very attractive feature for incorporation in a ventilation system of 6000 ft.^{3}/min. throughput with light gauge ductwork and low pressure blowers. Also, the general simplicity and safety of an open tower with a minimum of aqueous material present were factors deemed favorable to the spray tower.

It was also found in these tests of the small scrubber, that the caustic solution was quickly carbonated by the normal concentration of carbon dioxide in the air. This indicated that the spray contactor was a competitor of the packed tower for efficient absorption of carbon dioxide, and probably for other substances, such as acid vapors.

To gain more information as to the general applicability of the spray tower as a contacting device, a few tests on the removal of aerosols were made also.

*Presented at the 48th Annual Meeting of the Air Pollution Control Association at Detroit, Michigan, May 23-26, 1955.

Description of Equipment and Flow Performance

The scrubber is a box of welded 1/8-in. steel plate, 4 ft. square and 17 ft. long, with connections at each end for ductwork. It consists of 3 successive sections or stages, each having a bank of 4 hollow cone spray nozzles (Schutte-Koerting 622 C) impinging on cast iron throat pieces mounted on the 3 stage dividers. The tower rests on its side, and flow of gas and liquid is co-current and horizontal. Following the last stage is a simple array of staggered baffle plates and a 4 in. bed of 250 μ Monel fibers to provide de-entrainment. Finned tube steam heaters were used at the gas exit to raise the temperature of the gas and thus lower its relative humidity. Potassium hydroxide solution was circulated through the system with an iron centrifugal pump driven by a 7.5 horsepower electric motor. Three-inch black iron pipe conducted the solution to the spray header, and a 4 in. drain line returned the solution to a large stainless steel recycle tank, which also fed the pump. The layout is shown in Fig. 1.

The overall pressure drop of the tower is zero at 5400 ft.^{3}/min. gas flow and 101.0 gal./min. water flow. This is due to the fact that the high velocity co-current water spray imparts velocity to the air. This test was made with the tower open to the air at both ends. In another test, with an air through-put of 4000 ft.^{3}/min., the pressure drop across the stage (with the spray off) was 0.11 in. of water. The overall pressure drop in the vicinity of 6000 ft.^{3}/min. of air is zero with the spray on, and about 1 in. of water with the spray off.

Evaporation loss of water from the circulating liquid was 0.10 gal./min., calculated from the humidity data and confirmed by measurement of the loss of water from the circulating system. This loss is compensated for by discharging condensate from the steam heaters into the system.

Although observations through the Lucite windows of the tower spray section revealed considerable splashing of high speed droplets, no liquid entrainment was observed under any of the runs reported here. The highest humidity observed in the exit air was 89 %, and heating the air to 104°F reduced this figure to 33 %. Low relative humidity increases the lifetime of the "Chemical Warfare Service" filters which are part of the ventilation system.

TABLE I
Absorption In Single Nozzle Spray Tower (5-In. Diam.)
(Data from ANL-5015)

Run No.	Absorbed Gas	Air Rate lb./(hr.) (ft.^{2})	Liquid Rate lb./(hr.) (ft.^{3})	Contact Time Sec.	Total Inlet Conc. ppm (wt.)	Overall $K_G a$ lb.-mols/(hr.) (ft.^{3}) (atm.)
A3	F_2	344	1730	1.6	4510	24.2
A8	Br_2	218	1660	4.3	6500	12.1
B1	HF	214	1660	4.3	32,400	high (30)
B6	HBr	213	2900	2.5	6700	24.5
Interhalogen						
2	ClF_3	217	1660	4.3	19,170	11.9(a)
3	BrF_5	357	1730	1.6	13,520	29.2(b)
4	BrF_5	345	1730	1.6	11,600	28.3(b)
5	BrF_3	342	2900	1.6	2,415	21.4(b)
6	BrF_3	221	2900	2.4	1,400	12.1(b)
7	BrF_3	331	1730	1.6	864	13.4(b)
Average of Runs 2-7			2198		7249	21

(a) Value for fluoride absorption.
(b) Values for average fluoride and bromide absorption.

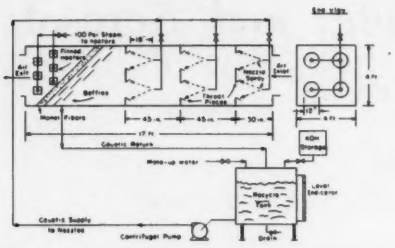

Fig. 1. Gas scrubber system.

Carbon Dioxide Absorption

As a preliminary check on the operation of the equipment, absorption tests of carbon dioxide from its normal atmospheric concentration were made, obtaining spray tower efficiencies which gave a comparison with other carbon dioxide absorbers. Absorption efficiency was obtained as a function of the process variables, namely, gas rate, liquid rate, and carbon dioxide, potassium hydroxide, and potassium carbonate concentrations.

The scrubber was equipped with tubes to withdraw metered gas samples from the inlet, exit, and 2 interstage points. Determination of the carbon dioxide concentrations were made by passing the streams through absorption trains. The dried gas stream was passed through 2 combination Ascarite — Anhydrone stages in which the Ascarite (solid sodium hydroxide plus asbestos) reacts with the carbon dioxide to produce water which the Anhydrone (magnesium perchlorate) absorbs. The gain in weight of the latter 2 stages gives a direct quantitative determination of the total carbon dioxide in the sample stream. A Pressovac pump was used to draw the air sample from the tower through the analysis train; the flow rate was measured with orifices which were calibrated with a wet test meter.

For all runs the air was at ambient atmospheric pressure and at room temperature. The entering carbon dioxide concentration was normal with an average value of about 500 ppm. by weight. The conditions and data from Run Series 1 are summarized and plotted in Fig. 2 which indicates the absorption behavior with respect to time and degree of carbonation. The first exit sample of the gas showed 275 ppm. (wt.) of carbon dioxide, thus corresponding to an absorption efficiency of 45 %. The exit concentration of carbon dioxide rose with increasing carbonate concentration in the liquid as the run proceeded.

In Run 2, all 12 nozzles were used, employing the entire 240 ft.^{3} of the tower (15 ft. of useful contacting length) The duration of this run was only 1 hr. in order to approach steady state absorption values for essentially uncarbonated solution. A decrease in absorption is shown with lower carbon dioxide concentration, in which the K_Ga varied as the 0.8 power of the concentration. A plot of data (obtained from interstage samples) is given in Fig. 3.

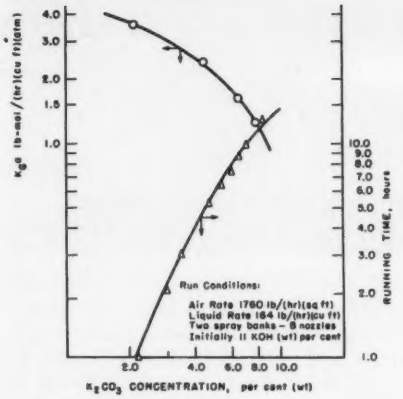
Run Conditions:
Air Rate 1760 lb/(hr)(sq ft)
Liquid Rate 164 lb/(hr)(cu ft)
Two spray banks – 6 nozzles
Initially 11 KOH (wt) per cent
RUNNING TIME, hours
K_2CO_3 CONCENTRATION, per cent (wt)

Fig. 2. Absorption of carbon dioxide in a spray tower; variation of K_Ga with carbonate concentration.

A series of runs at several liquid and gas rates were made, using only a single bank of 4 nozzles. The general conditions were the same as Run 2, except that only ⅓ of the tower was used, and in 2 runs lower potassium hydroxide concentrations were used. Plots of K_Ga versus gas rate, liquid rate, and potassium hydroxide concentration are shown, respectively, in Fig. 4, 5, and 6. No effect of the gas rate is evident, but K_Ga increases with the 1.6 power of liquid rate. The K_Ga apparently drops off at an increasing rate below 5% potassium hydroxide.

The values of absorption efficiency and overall mass transfer coefficient K_Ga were calculated from the measured inlet and exit carbon dioxide concentrations. The absorption efficiency E, was calculated as the per cent absorbed of carbon dioxide entering the scrubber section. In terms of inlet concentration, C_1, and exit concentration, C_2, $E = \dfrac{C_1 - C_2}{C_1}$

The equation defining K_Ga is:

$$\frac{G}{M_{ave}}\,dy = -K_Ga\,(y - y^*)\,PdH$$

where G = mass rate of flow of gas, lb./(hr.) (ft.^{2})

M_{ave} = average molecular weight of the gas

y = mol fraction of absorbed gas in the differential element of height, dH, of the tower.

y^* = mol fraction of absorbed gas at equilibrium with the liquid phase at that point in the tower.

P = total pressure in atmospheres

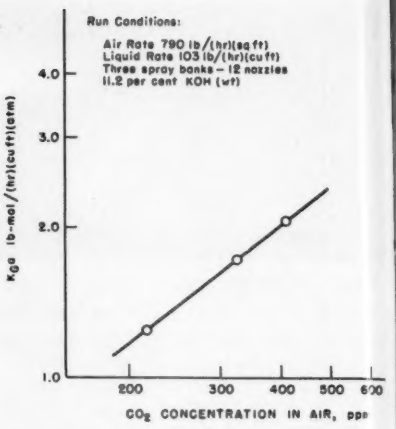
Run Conditions:
Air Rate 790 lb/(hr)(sq ft)
Liquid Rate 103 lb/(hr)(cu ft)
Three spray banks – 12 nozzles
11.2 per cent KOH (wt)
K_Ga lb.-mol/(hr)(cu ft)(atm)
CO_2 CONCENTRATION IN AIR, ppm

Fig. 3. Absorption of carbon dioxide in a caustic spray tower; variation of K_Ga with CO_2 concentration.

H = total height of tower, ft.

K_Ga = overall mass transfer coefficient, lb.-mols./(hr.) (ft.^{3}) (atm.).

In the present case of absorption with chemical reaction, y^* may be taken as zero, and, for the dilute concentrations of absorbable component used,

$$M_{ave} = M_{air} = 29, \text{ and } \frac{y_1}{y_2} = \frac{C_1}{C_2}$$

Also, for atmospheric pressure P=1. Using these simplifications, and introducing E, we have upon integrating

$$K_Ga = \frac{2.3\ G}{29\ H}\ \log\ \frac{1}{1 - E}$$

The residence time (or contact time) of the gas in the tower, τ_c, is given in seconds by the expression

$$\tau_c = \frac{3600\ H\ \rho}{G}$$

where ρ is the density of the gas in lb./ft.^{3}.

In packed columns, the HTU, which for this case is the ratio of G to K_Ga, is often more nearly constant than K_Ga over a range of gas rates. This is due mainly to the fact that K_Ga increases with the gas rate in these cases; however, in spray towers, this situation does not hold. The K_Ga is used here throughout as the measure of absorption performance.

A spray tower is essentially a volume in which gas flows through a dispersion of liquid droplets. Usually these droplets are moving at a velocity much greater than that of the gas stream. Thus the relative speed of the 2 phases in contact is a characteristic of the liquid flow and spray nozzle rather than the gas flow and cross sectional area of the tower. On the other hand, the gas flow and tower volume determine the contact time and

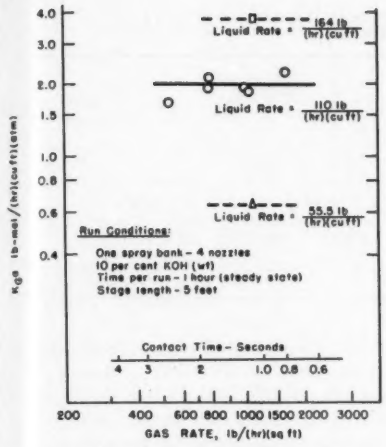
Liquid Rate = 164 lb/(hr)(cu ft)
Liquid Rate = 110 lb/(hr)(cu ft)
Liquid Rate = 55.5 lb/(hr)(cu ft)
Run Conditions:
One spray bank – 4 nozzles
10 per cent KOH (wt)
Time per run – 1 hour (steady state)
Stage length – 5 feet
Contact Time – Seconds
GAS RATE, lb/(hr)(sq ft)

Fig. 4. Absorption of carbon dioxide in a caustic spray tower; variation of $K_G a$ with gas rate.

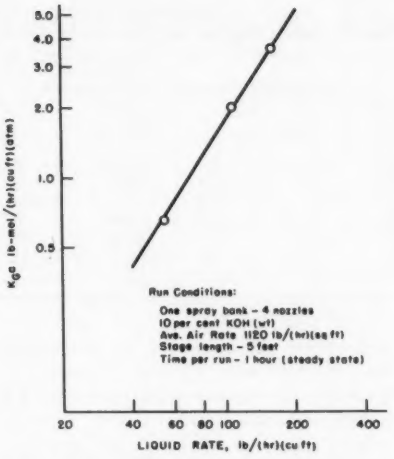
Run Conditions:
One spray bank – 4 nozzles
10 per cent KOH (wt)
Avg. Air Rate 1120 lb/(hr)(sq ft)
Stage length – 5 feet
Time per run – 1 hour (steady state)
LIQUID RATE, lb/(hr)(cu ft)

Fig. 5. Absorption of carbon dioxide in a caustic spray tower; variation of $K_G a$ with liquid rate.

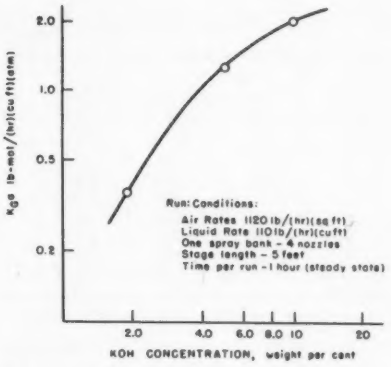
Run Conditions:
Air Rates 1120 lb/(hr)(sq ft)
Liquid Rate 110 lb/(hr)(cu ft)
One spray bank – 4 nozzles
Stage length – 5 feet
Time per run – 1 hour (steady state)
KOH CONCENTRATION, weight per cent

Fig. 6. Absorption of carbon dioxide in a caustic spray tower; variation of $K_G a$ with KOH concentration.

hence the fraction absorbed at any given liquid rate.

The actual droplet velocity in the nozzle used in these tests was measured as 48 ft./sec. at 2.4 gal./min. flow and 66 ft./sec. at 3.5 gal./min. The observations were made with high-speed motion pictures at 800 frames/sec. This Schutte-Koerting nozzle (type 622-C) imparts a rotary movement to the liquid by means of a helix in the entrance section of the body of the nozzle. When the liquid leaves the nozzle it forms a 30° hollow cone. This stream is in high turbulence, breaking up into irregular sheets and droplets within about an inch of the nozzle, but holding the overall conical configuration to a length of about 2 ft., depending on liquid rate. The motions were not completely stopped at 800 frames/sec., but a large number of droplets of 0.004 to 0.028 in. in diam. were seen. The length of the cone, the density of droplets, and their speed, all increased with liquid flow through the nozzle. This, of course, amounts to a large increase in interfacial area. The practical range of flows through a single nozzle is between 1.0 and 7.0 gal./min. Above this range the pressure drop increases rapidly, making the pumping requirements uneconomical. Below this range, the cone size and the interfacial area is only a small fraction of the nozzle capabilities. In the single nozzle 5-in. diam. spray tower tests summarized in Table I, the liquid rates/nozzle were between 1 and 2 gal./min. In the present scrubber tests, the range was between 2 and 7 gal./min./nozzle.

From the above considerations, it is evident that the gas rate in general does not influence the relative phase velocity in spray towers, hence neither the film resistance nor the $K_G a$. The liquid rate strongly influences the $K_G a$, but this comes about by affecting the interfacial area rather than the film resistance, since within the droplet the liquid is static, whatever the flow rate may be.

Absorption of atmospheric carbon dioxide in a 12-in. diam. tower, 7.8 ft. long, packed with ¾-in. Raschig rings, has been reported by Spector and Dodge[2]. Both sodium and potassium hydroxide at about 10% (wt.) were used; the potassium hydroxide was found to be slightly superior in absorption performance. The absorption studies were carried on with solutions less than 15% carbonated, since up to this point carbonation had negligible effect on absorption. The percentage absorbed of entering carbon dioxide was, of course, higher in the case of the packed tower, corresponding to the longer contact time. On the other hand, more gas was put through the spray tower, with a lower pressure drop. The fact that the $K_G a$ values were comparable is rather interesting, considering the different means of producing interfacial area.

In this report of Spector and Dodge, certain conclusions were drawn about the absorption process:

1. A rather low order of dependence on the gas rate is shown by $K_G a$, although the gas film is shown to be at least partially controlling because $K_G a$ decreases with increasing partial pressure of the inert gas.

2. The liquid film is not expected to be controlling, since the chemical reaction involved is fast and complete. Nor do the data show the liquid rate to have much influence, the small effect shown probably being due to increased interfacial area. On the other hand, the hydroxide concentration and the liquid temperature show a strong effect on $K_G a$.

In the present spray tower tests, the carbon dioxide concentration effect and the hydroxide effect are confirmed. No effect of the gas rate was found, but this is a characteristic of spray contacting more than of the carbon dioxide-caustic system. A strong effect of liquid rate was shown, quite definitely due to interfacial variation. The temperature effect was not investigated.

Halogen Vapor Absorption

The primary purpose of the tests of absorption of halogen vapors from air in this scrubber was to measure its effectiveness in removing toxic halogen vapors that might be released into the ventilation system in which the scrubber is installed. In addition, the data obtained, together with the previous halogen absorption data from the smaller spray scrubber[1], was to provide information on scale-up factors in spray tower design.

Introduction of halogen vapors into the scrubber was accomplished by passing a preheated air stream of about 2 ft.³/min. through a small tank containing the halogen. The vapor mixture was then introduced into the entrance air duct to the scrubber.

Sampling of the air stream at the exit and entrance to the tower was performed by withdrawing metered gas streams through a 3-stage bubbler containing 10% by weight of potassium hydroxide. Halogen concentrations were then determined on the basis of chemical analysis of halides in the bubbler solution. Fluoride analysis was performed spectrophotometrically using Thoron reagent

[2] Spector, N. A., and Dodge, B. F., *Trans. Am. Inst. Chem. Engrs.*, 42, 827 (1946).

[1] Liimatainen, R. C., and Levenson, M., "Absorption of Some Halogen Gases from Air by a Limestone Bed and a Spray Tower,"—ANL-5015.

TABLE II
Absorption Of Interhalogens In A Horizontal Spray Tower

Run No.	Absorbed Gas	Air Flow lb./(hr.) (ft.²)	Liquid Flow lb./(hr.) (ft.³)	Contact Time, Sec.	Absorbing Liquid (Conc. Wt. %) KOH	K_2CO_3	Halogen Conc. (ppm. by Wt.) Inlet Total	Exit F	Exit Br	Overall Eff. of Absorption (percent) F	Br	K_Ga lb.-mols./(hr.)(ft.³)(atm.) F	Br
1	BrF_3	1195	109	3.36	7.5	4.3	91.2	3.4	15.5	92.0	69.0	6.6	3.4
2	BrF_3	1195	109	3.36	7.5	4.3	200.0	0.0	3.6	100.0	97.0	12.1[a]	10.5
3	I_2	1690	109	2.38	6.1	2.1	114.0	4.8(total I_2)		95.8 (I_2)		12.3 (I_2)	
4	BrF_5	1690	109	2.38	5.1	1.4	458.0	3.5	0	98.6	100.0	16.5	20.7[a]
5	BrF_5	1690	124	2.38	3.3	2.2	585.0	0	29.4	100.0	89.0	22.3[a]	8.5
6	BrF_5	1195	109	3.36	2.9	3.0	680.	25.7	14.1	93.0	95.5	7.3	8.5
Average		1442	112				355.					13.	10.

[a] Calculated assuming 1.0 ppm. rather than 0 as the exit concentration.

in the method described by Horton *et al*[3]. Bromide analysis was done by a standard Volhard titration. Iodine analysis was done spectrophotometrically after extraction into carbon tetrachloride.

Two runs were made with bromine trifluoride, 3 with bromine pentafluoride, and 1 with iodine. All runs were made with the full 12 nozzles using an aqueous potassium hydroxide spray. Two different liquid rates and 2 gas rates were used, all at 1 atmosphere total pressure and room temperature. The range of inlet concentration was from 91 to 680 ppm. (wt.). Fluoride absorption efficiencies ranged between 92.0 and 100% and bromine efficiencies from 69 to 100%. The data are summarized in Table II.

Calculations of K_Ga were made in the manner described previously. However, because some samples showed zero concentration in the exit stream, the K_Ga could only be calculated by assuming a finite exit concentration; a value of 1 ppm. was chosen. Because of this situation and a general scattering of the data, no clear quantitative variation of K_Ga with gas or liquid rates can be shown, although there is a rough upward trend with both stream rates. On the other hand, a rather definite increase of K_Ga with inlet concentration is shown by the plot in Fig. 7. K_Ga appears approximately proportional to the 0.7 power of concentration.

[3] Horton, A. D., Thomason, P. F. and Miller, F. J., *Anal. Chem.*, **24**, 548 (1952).

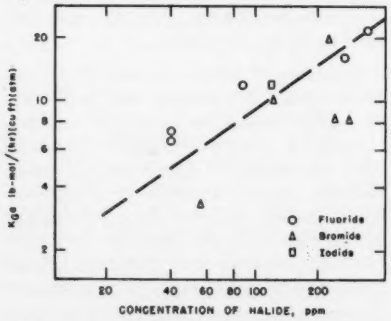

Fig. 7. Absorption of bromine fluorides and iodine in a caustic spray tower; variation of K_Ga with inlet concentration.

The average of the K_Ga values for fluoride absorption from the bromine fluorides was 13 lb.-mols./(hr.) (ft.³) (atm.); for bromide, 10. The single value for iodine absorption was 12. These values compare with those of the single nozzle scrubber data shown in Table I as follows:

1. The K_Ga for elemental iodine (in the large scrubber) is the same as for bromine (in the small scrubber).
2. The K_Ga for elemental fluorine (in the small scrubber) is about twice this, or 24 lb.-mols./(hr.) (ft.³) (atm.).
3. The averaged K_Ga for both fluoride and bromide absorption from the bromine fluoride was 21 lb.-mols./ (hr.) (ft.³) (atm.) in the small scrubber, or about 75% higher than the comparable figure obtained in the present tests with the large scrubber.

It is not surprising that the K_Ga for the small tower was somewhat higher, since both the average liquid rate and inlet concentration were substantially higher in those runs (see Tables I and II).

A comparison of the mass transfer coefficients attained with interhalogens to those for carbon dioxide absorption shows that halogens had the higher coefficients. It is believed that this difference is due to a more rapid reaction between the halogen and the caustic than between the carbon dioxide and the caustic.

Aerosol Tests

In order to observe the performance of the spray tower as a contacting device to remove aerosols, tests were made with fumes of a size range commonly encountered in air cleaning practice.

Metered gas samples were taken from the inlet and exit streams bearing the aerosols and drawn through a millepore membrane filter. This filter removes particles greater than 0.1 μ with nearly 100% efficiency[4]. Counting and sizing the particles on the filter was done with a microscope of 900 diam. magnification, by the oil immersion method with transmitted light. An electron microscope was also used in the case of the sodium oxide.

Ammonium chloride aerosol was formed by passing a heated air stream first through concentrated hydrochloric acid and then over a concentrated ammonia solution. A second air stream was used to dilute the smoke formed and carry it to the gas inlet to the scrubber. All 12 spray nozzles were used in the 2 ammonium chloride runs.

Sodium oxide aerosol was produced by igniting some of the metal in the inlet section of the tower. The aerosol then passed through the last 2 sections of the tower with 8 nozzles operating.

The run data and conditions for all 3 runs are shown in Table 3. The ammonium chloride aerosol had a mean diameter of 0.5 μ; the efficiency of removal was 57% for a residence time of 4.5 sec., and 44% for a residence time of 3.2 sec. The sodium oxide had a mean particle diameter of 0.04 μ using an electron microscope; the mean diam. determined at 900 x was approximately 0.2 μ. A figure of 0.1 μ might be used as the mean sodium oxide particle diameter thus giving less weight to the 900x microscope determination since with that device the particle size was very nearly at the limit of detectability. The efficiency of sodium oxide removal was found to be 35% for a residence time of 5.8 sec. For both aerosols, no preferential size removal was shown.

The aerosol collection efficiencies for the spray tower are substantial, although not too high when compared to the performance given by common filters. Spray towers usually have efficiencies less than 20% for particles 1 to 5 μ, accord-

(Continued on page 49)

[4] First, M. W. and Silverman, L., *A. M. A. Arch. Ind. Hyg. and Occup. Med.*, **7**, 1 (1953).

[5] First, M. W. *et al.*, "Air Cleaning Studies Progress Report", NYO-1581, (1951), p. 43.

Electric Furnace Ferrosilicon Fume Collection*

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Residents of many urban centers are becoming increasingly aware of the obscuring effect of fume and smoke discharge from power, metallurgical, chemical, and other industries; and they, as well as the legislatures of these affected cities, are agitating for cleaner air. Management's most pressing problem is to find an economical way to reduce process effluents in response to the growing pressure from population and legislative demands. The removal must be done, if possible, without handicap to the current operation, since the costs of relocating are often excessive or prohibitive.

In fume recovery or disposal, an important item to consider is whether or not the material being discharged has any value. If it has commercial value, the cost of its recovery may offset or aid amortization. For this reason, in making a study of the specific problem in hand, a major factor was the nature of the material emanating from the stack: in particular, its particle size, size range, and its chemical and physical composition, as well as its potential value and utility when recovered (in either a wet or dry state). Should the product have no commercial value, it must be disposed of at minimum cost in a way to prevent recontamination.

Initial studies were therefore made to determine stack concentrations and volumes of material evolved from the operations. The next phase of the study concerned the physical and chemical nature of the collected fume. The third portion of this paper describes the wet and dry collector studies undertaken to recover the fume.

Cleaning Requirements for Ferroalloy Furnace Operation

The basic need for any effluent collection equipment is the highest possible efficiency and the lowest tolerable resistance when the power consumption involved is considered. Since the electric furnace effluent is largely composed of fume of small size (less than 0.5 μ), it has high light obscuring properties, and even low concentrations will cause some loss of visibility and be evident to nearby residents. The permissible limit for fly ash emission in many cities is based on a weight value approx. 0.4 gr./ft.^{3}, but the smoke density values are dependent upon a shade of color. In the case of the Los Angeles County code, emission is restricted to lbs./lb. of material processed/hr. basis (but not exceeding 40 lb./hr. for any one given plant operation).

If an average particle size of the fume from ferrosilicon alloy electric furnaces is assumed to be 0.4 μ (as shown later, this is the approximate mean size) and an average loading of 1 gr./ft.^{3} (stp), each cubic foot of stack gas will contain approximately 75×10^{10} particles (based on assumed, and confirmed, spherical shape and a standard deviation of unity). When it is realized that the air in metropolitan areas, which are also general industrial areas, contains approximately 5×10^6 particles, the tremendous light scattering effect of this concentration becomes apparent. Consequently, nearly 100% collection would be necessary to equal the average concentration. Fortunately, however, discharge from a high point above ground (50 to 100 ft.) will result in at least a thousandfold dilution, or the stack concentration reaching the ground in the foregoing case might result in a ground concentration of 75×10^7 particles. If the concentration at the source could be reduced by a factor of 100 (99% efficiency of collection), then a concentration of 75×10^8 particles would be diluted to 7.5×10^6 which would be very satisfactory. An efficiency of 90% (factor of 10 decontamination) at the source would result in a discharge of 75×10^9 particles which upon dilution yields 75×10^6 which is still 15 times the general air value. Another approach to this consideration is to use the value of concentration of 0.005 gr./ft.^{3} for the value of a visible effluent as cited by Kayse[1]. To attain this value with an average loading of 1 gr./ft.^{3} would require an efficiency of 99.5%. Since the foregoing value is not based on any reported size of fume particles, it is felt that the numbers' approach given previously is more reliable.

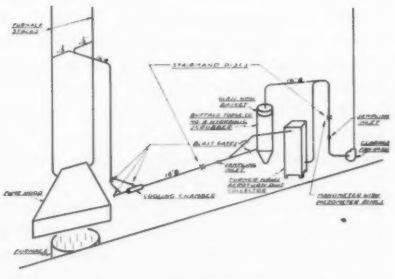

Fig. 1. In order to determine the gas temperatures and volumes discharged and fume loadings at different points, the furnace stack was sampled at the locations shown in the schematic drawing. Taps were made at 10, 20, and 30 ft. in the stack. The experimental dust collecting unit, as well as the stacks, is shown.

These calculations serve to indicate the desirability of thorough cleaning, preferably at the source, and with efficiencies well above 90%, preferably above 95% (dilution 1:20). One of the most important items in any control program is to reduce the concentrations as close to their sources as possible. The use of better furnace design, deeper coverage over the electrodes, and the prevention of *blows* or breaks in the surface all help to reduce dissemination; consequently, all these improvements should be made, if possible, to cut down the effluent load. In addition, in order to minimize the volume of contaminated air that has to be cleaned, the furnace should be enclosed as much as possible.

Test Arrangements

Before fundamental studies with collectors were made, a furnace stack selected for the test program was sampled to determine the gas temperatures and volumes discharged and the fume loadings at different points. Taps were made at 10, 20, and 30 ft. in the stack as shown in Fig. 1. Samples were obtained with the stack sampling device shown in Fig. 2 and described in detail elsewhere[2]. Twenty samples were ob-

* Reprinted from the *Journal of Metals*, 7, 1327-35 (December 1955) published by the American Institute of Mining, Metallurgical, and Petroleum Engineers.

(1) J. R. Kayse: Graphical Selector for Air Cleaners. *Heating and Ventilating* **50**, 80 (1953).

(2) R. Dennis, G. A. Johnson, M. W. First, and L. Silverman: How Dust Collectors Perform. *Chem. Eng.* **39**, 196 (1952).

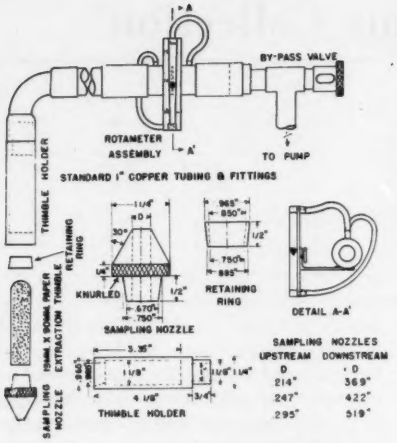

Fig. 2. Device, described in detail elsewhere, used for stack sampling at the locations indicated in Fig. 1 is shown in this schematic diagram. The unit utilizes paper or glass cloth and fiber thimbles. Diameters of the upstream sampling nozzles are 0.214, 0.247, and 0.295 in.; diam. of the downstream sampling nozzles are 0.369, 0.422, and 0.519 in. Other specifications are given in the diagram.

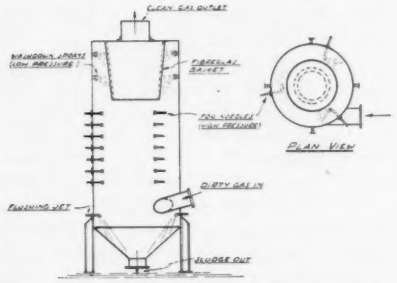

Fig. 3. For wet collection, a pilot-size spray-type scrubber, rated at 4000 cfm., was obtained. This hydraulic fog scrubber is housed in a steel tower 4 ft. diam. and 15 ft. high. Diagram shows the schematic arrangement of the test equipment, and the cross-section of the wet scrubber is shown in detail.

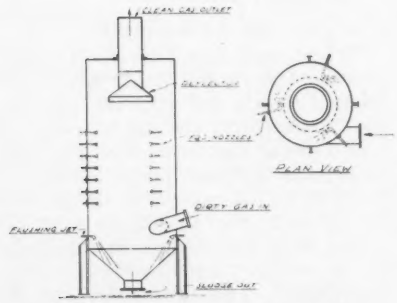

Fig. 4. Second diagram of the scrubber unit shows the schematic arrangement of the Fiberglas pack as a final separator in the spray tower unit. By providing a removable baffle top which could be replaced with various final separators and eliminators, the performance of a number of types of final separators and Fiberglas filters could be evaluated.

tained and analyzed for loading and particle size; mean results are presented in Table I. Mean loadings over a typical period of operation varied widely from 0.5 to 2.7 gr./ft.^{3} with an overall mean of approximately 1 gr./ft.^{3}. Stack temperatures ranged between 240° and 330°C. Little effect of point of take-off on temperature or loading was observed.

These data indicated it was desirable to branch from the stack at the 20 ft. level in order to get ambient air cooling and to take advantage of elutriation or settling in the stack. The arrangement and location for the wet collector was made so that other devices could be inserted into the line for test purposes. An equal connection to both stacks was made as indicated in Fig. 1. This arrangement made it possible to observe a number of conditions. All of the air could be withdrawn directly from the stack or air could be obtained at varying temperatures and loadings by opening the dilution bypass valve, a flexible arrangement for varying both temperature and loading. To obtain uniform isokinetic sampling, a sufficient number of diameters (8 to 12) were provided before the sampling point upstream of the collector installation and downstream of the collector. The 2 ducts were provided with Stairmand disks[3], devices which provide a constant turbulence and a uniform cross-sectional loading at the sampling point. Single samples could then be taken which are representative of the cross-stream loading. In this initial test arrangement, it was possible to study the scrubber and at the same location dry collectors or any other units for experimental evaluation.

Particle Size and Chemical Composition

A number of the samples indicated in Table I were analyzed for size and composition. Optical microscope sizes were made with oil immersion and it was apparent that a number of the particles were probably far below the visibility range even though mean sizes were found by extrapolation from 0.2 to 0.5 μ. These particles were not sized under the electron microscope in this investigation but samples of fume from a similar furnace had a mean particle size of 0.3 μ by electron micrograph analysis which agreed quite well with the optical sizing. The optics indicated that the particles were spherical and this was also easily evident in the electron micrographs. Examination of samples at several thousand diameters indicated that the silica fume was completely spherical and formed chains. This chaining action could account for the extremely fine particles, *i.e.*, those less than a thousandth of a micron, which could be seen in the background forming larger aggregates which also appeared in the light microscope as spheres close to the limit of resolution.

Under normal furnace operations, the particle size distributions with a mean geometric dimension of 0.3 to 0.4 μ represented average conditions. Particle sizes varied from 0.01 to 4 μ. During blows or breaks in the furnace surface, particles as large as 40 μ were obtained and identified. These were presumably carried up the stack, since the velocity was approximately 2000 ft./min. This would sustain particles much larger than 200 μ.

A study of the chemical properties of the material indicated that fume from 50% ferrosilicon furnace operation showed a loss on ignition of approximately 1.3%, and at least 92.8% was in the form of dehydrated silica. Optical analysis indicated that the material was predominately amorphous silica with traces of iron oxide and it confirmed the chemical analyses.

In addition to the chemical and physical analysis, spectrographic and X-ray diffraction analyses were made. Fume samples indicated the presence of silicon, iron, aluminum, calcium, magnesium, manganese, copper, and titanium. Lead, tin, and zinc were present in trace amounts and sodium was present in slightly larger than trace amounts. The percentage of silica varied between 63 and 88 for 3 different fume samples, whereas the iron concentration varied between 8 and 25%. The bulk of the sample, therefore, by spectrographic analysis is in the form of silicon and iron. By weight conversion, in terms of silica as silicon dioxide and iron as iron oxide, calculation indicates the material was in the form of these oxides. A comparison with the furnace product ferrosilicon materials showed that some elements present in the ferrosilicon alloy did not appear in the fume. These included chromium, carbon, nickel, phosphorus, and sulphur. These materials, in a reducing atmosphere, apparently do not volatilize and appear as aerosols. They could also have been adsorbed as gaseous materials on the fume and disappear under normal spectrographic procedures.

To determine if the silica was in the form of SiO, SiO_2, or possibly as elemental silicon, an X-ray diffraction analysis was made on the spectrograph fume samples.

X-ray diffraction analysis indicated that the fume samples were completely different from the ground ferrosilicon.

[3] *Engineering* London **152**, 141, 181 (1941). Data contributed by C. J. Stairmand.

Three fume samples that were studied indicated the presence of a small amount of quartz. This free silica could be material carried from the furnace during blows or by normal entrainment of atmospheric dust which did alter its crystalline structure. None of the fume samples indicated the presence of ferrosilicon but a crystalline material in the fume was present in traces which could not be identified. The X-ray diffraction library used is extensive and comparisons were made with iron oxides, iron silicates, calcium silicates, and calcium carbonates; and many other potential compositions were unsuccessful. Crystalline substances, however, were only present in small amounts and do not constitute a problem which could affect material purity.

In addition to the foregoing tests, some simple physical and chemical measurements were made. The bulk density of the collected material was quite low and varied between 4 and 10 lb./ft.^{3}. This varied, with aging, compacting, or degasifying, and any of these could increase the bulk density several-fold. Dispersion of fume in triple distilled water indicated a solubility between 1½ and 4%, depending upon whether the sample had been collected before or after the wet collecting unit. Surface tension depression of the fume in solution was observed with capillary surface tension apparatus. The material apparently has some detergent effect and produced a 10% reduction in surface tension. The pH of the dispersion was slightly basic and varied between pH 8.2 and 9.

Wet Collector Studies

A pilot-size spray-type scrubber rated at 4000 ft.^{3}/min. capacity was obtained for wet collection studies. This unit, shown in Fig. 3, is a steel tower 4 ft. diam. and 15 ft. high with a round inlet (later changed to rectangular) at the bottom. The entering air stream circulates centrifugally through this tower past a series of nozzles which project across the circulating air stream at various locations. A *Christmas tree* central manifold made it possible to place a number of nozzle locations, orientations, and types of nozzles in the circulating vertical air stream. In the usual scrubber of this type, nozzles are mounted at the wall, but with this unit such location can be made from the inside. A number of tests were made with variable nozzle conditions. The effect of nozzle pressures and subsequent droplet sizes were also investigated.

A baffle top was provided which could be removed and replaced with various types of final separators and eliminators. In this study, the performance of a number of types of final separators and Fiberglas filters was obtained; see Fig. 4. In evaluating the wet scrubber performance, a series of 46 different test arrangements were investigated. With each arrangement at least 5 individual runs were obtained and averaged. The test conditions, with results obtained, are indicated in Table II.

It will be seen from the complete Table II that practically all possible physical arrangements of the scrubber were evaluated. Conclusions presented in this report are based on results obtained with the variable conditions observed. During these tests, a wide variety of furnace conditions were encountered. A 50% ferrosilicon alloy was in production at all times with typical fume conditions resulting from normal operations. Occasional blows in the furnace were an integral part of the sampling conditions. As mentioned previously, the effect of blowing and furnace operations affects the grain loading of the fume as well as its particle size. This would therefore account for variability in each test series. Early in the study, it was observed that a fishtail inlet inserted in the round inlet was ineffective and was removed. The circular inlet was later changed to a tangential rectangular opening and observations were made with an inlet velocity of 4000 fpm.

Based on the wet collector studies, the following conclusions may be drawn:

1—This device, with optimum nozzle location, type, and pressure conditions, provides a simple collecting unit of low resistance (less than 2 in. water) with a maximum collection efficiency of approximately 70%.

2—Higher efficiencies were obtained by adding to this unit a Fiberglas conical basket separator with various packings, but it was found that this soon *plugged* and could not be maintained in continued operation without removal and replacement. It thus would be impractical for large scale use. The material caught on the filter set into a hard crust which could not be removed by washing if allowed to dry.

TABLE I

Stack Loadings and Sizes During Typical 50% Ferrosilicon Alloy Operations

Sample Nos.	Location	Furnace Condition	Loading, gr./ft.^{3}, Stp.	Particle Size	
				Mean, μ	Standard Deviation
1	In stack, 10 ft. above furnace	45 min. before tap	1.32	0.2 to 0.3	2 to 4
2		At tap time	2.05	—	—
7		At tap time	1.94	—	—
			Mean 1.79		
3	In stack, 20 ft. above furnace	At tap time	1.06	—	—
4		20 min. after tapping	0.42	—	—
6		1 hr. 45 min. after tapping	2.33	—	—
9		End of tapping	0.84	—	—
13		During tapping	0.84	—	—
17		During tapping	0.74	—	—
18		During charging	1.73	—	—
20		During tapping	0.52	0.53	2.2
			Mean 1.06		
8	In stack, 30 ft. above furnace	At tap time	0.11	—	—
11		At tap time (blow through)	2.72	0.18 to 0.28	2 to 4
12		At end of tap	1.57	—	—
19		During tapping (blow through)	1.99	0.43	2.2

TABLE II(4)
Wet Collector Studies—Experimental Hydraulic Scrubber

Series	Number of Tests	Air Flow, cfm. Stp. Range	Pressure Loss, In. of Water Range	Collector Conditions, Range					Loading Range gr./ft.³ Stp.		Efficiency Range, Wt. %
				Entering Temperature, °C	Leaving Temperature, °C	Nozzle Pressure and Flow			Inlet	Outlet	
						Air, Psi	Water, Psi	Water, gpm.			
B	8	2800	1.9 to 2.2	150 to 180	20 to 27	30	9 to 13	3.0 to 5.0	0.144 to 1.675	0.077 to 0.530	46.4 to 77.2
E	5	2800	1.1	160 to 165	22 to 25	30	19	10	0.506 to 1.50	0.141 to 0.407	66.5 to 81.4
F	4	2800	0.54 to 0.62	160	27 to 28	15	13 to 15	8.5	0.980 to 2.01	0.289 to 0.677	42.6 to 78.6
G	9	2800	0.52	145	17	25	14 to 15	8	0.335 to 0.856	0.078 to 0.266	37.3 to 85.6
H	5	2800	0.38	160	50	—	15 to 20	3 to 3.75	0.139 to 2.27	0.153 to 1.50	9.5 to 55.0
J	5	3260	0.8	160	80	—	—	—	0.64 to 1.77	0.58 to 1.08	9.9 to 39.4
K	5	2800	1.5	160	24 to 25	30	30	12.6 to 15.0	0.497 to 1.04	0.157 to 0.409	58.4 to 68.4
M and N	10	2800 to 3010	0.5 to 1.1	170 to 200	33 to 40	30	14 to 20	4.7 to 5.0	0.35 to 3.95	0.14 to 1.05	50.0 to 73.1
O and P	9	2800	0.45 to 1.25	165 to 180	34 to 44	30	20	1.2 to 8.6	0.16 to 1.04	0.038 to 0.585	22.1 to 76.0
Q	5	2800	2.7 to 3.0	160 to 170	31 to 34	30	16	8.3	0.339 to 2.31	0.044 to 0.24	84.7 to 87.5
S	5	2800	0.55	167 to 173	31 to 32	28	18	7.5	0.73 to 1.610	0.085 to 0.433	70.0 to 95.0
V	5	2800	0.96 to 2.85	97 to 155	10 to 19	—	400	20	0.583 to 1.600	0.028 to 0.365	77.0 to 95.3
X	6	1650	5.2 to 6.8	130 to 168	12 to 17	—	400	20	0.483 to 5.70	0.120 to 1.02	56.0 to 82.2
Y	6	2590	0.64 to 0.68	160 to 192	21 to 24	—	400	20	0.518 to 1.645	0.167 to 0.588	53.9 to 64.2
Z	7	2630	2.3 to 2.6	160 to 177	21 to 23	—	400	20	0.394 to 2.188	0.167 to 0.934	47.3 to 75.9
A-1	6	2650	2.3 to 2.6	170 to 220	16 to 28	—	400	20	1.202 to 5.340	0.433 to 2.030	58.5 to 63.8
D-1	6	2800	1.9 to 3.0	137 to 163	7 to 8	—	400	20	0.561 to 2.085	0.154 to 1.172	43.7 to 77.8
G-1	5	2800	7.2 to 7.4	140 to 148	5	—	400	20	0.463 to 1.742	0.091 to 0.237	80.4 to 88.4
I-1	10	2760	0.48	163 to 173	9 to 10	—	400	20	0.220 to 2.120	0.026 to 0.356	78.9 to 88.3
K-1	5	2760	0.38 to 0.40	148 to 152	8 to 9	—	400	20	0.163 to 1.475	0.035 to 0.226	78.6 to 84.7
M-1	7	2630	0.77 to 0.78	171 to 186	18 to 19	—	400	20	1.015 to 2.820	0.399 to 0.910	59.6 to 67.8

Table II Continued

Remarks and Observations on Test Arrangements

Nozzle Positions	Description
A—20° from tangent B—10° down C—10½ in. from wall D—Equal distances E—90° apart	Fishtail inlet, baffle top, 40 air-jet target nozzles spaced over entire height of tower. Average efficiency 59.8%
A—Tangential B—10° down C—10½ in. from wall D—Equal distance E—90°apart	40 air-jet modified nozzles (target removed, water jet retracted); round inlet only. Average efficiency 74.3%
Same	Same as *E* but with reduced air and water pressures. Average efficiency 64.5%
A—Tangential B—45° up C—10½ in. from wall D—Equal distance E—90° apart	Circular inlet, baffle top, 40 modified nozzles (as in E); considerable carry-over in these tests. Average efficiency 64.0%
	Cooling spray only, nozzles placed 6 in. from flange into collector, spray was concurrent to flow. Average efficiency 18.5%
	No nozzles or piping; operated as dry cyclone. Circular inlet; baffle top. Average efficiency 23.5%
A—Tangential B—Horizontal C—10 in. from wall	Circular inlet, baffle top, 40 air-jet modified nozzles (see G). Modified nozzles concentrated in lower third of tower. Average efficiency 62.1%
A—Tangential B—Horizontal C—10 in. from wall D—Lower 12 nozzles through 270° of turn E—Top 28 at 90°	Rectangular inlet, Fibreglas basket 1 in. thick filter top (fiber size 100 μ) with washdown sprays; lower 12 nozzles; spraying systems set-up No. 23 located in first 270° of circumference. Other nozzles modified as K. Average efficiency 60.1%
Same as *M* only lower bank of 12 operated	Rectangular inlet; Fiberglas basket cone frustum filter top as above; only 12 lower nozzles in operation; resistance increased throughout test indicating plugging of filter top. Average efficiency 43.6%
Nozzles same as *E*	Rectangular inlet; Fiberglas basket cone frustum filter top filled with mixed 10 to 250 μ glass fibers; spraying system nozzles replaced with modified air jets; resistance did not level off. Average efficiency 86.1%
	8 in. Fiberglas in basket compressed to 5 in.; 28 hr. continuous operation; 40 air-jet nozzles. Average efficiency 76%
	Changed to John Bean No. 2½; penetrating spray nozzles (40 nozzles) at end of 183 hr. Average efficiency 83%
	Same basket as above; 200 hr. operation. Average efficiency 70%
	Basket packed with 250 μ Fiberglas 6 in. compressed to 4.5 in.; 40 John Bean nozzles, 3 hr. service on basket. Average efficiency 61.4%
	Same basket as above with 28 hr. of operation, most of bottom spray bank plugged. Average efficiency 57.3%
	Resistance across unit reduced from 10 to 2.2 in. water gage before test; washdown sprays in operation during test. Average efficiency 60.6%
	Same basket as above with 44 hr. service. Average efficiency 73.8%
	Test run after washing basket; unit resistance lowered from 9 to 7.2 in. water gage; 48 hr. service on basket. Average efficiency 84.2%
	Basket packed with 4 layers of 250 μ Fiberglas compressed to 3½ in.; 24 hr. of continuous service on new basket at time of test. Average efficiency 82.3%
	Same filter basket as *I*-1 and 96 hr. of continuous service. Average efficiency 81.8%
	New basket as above; 96 hr. service on filter. Average efficiency 62.1%

3—The wet collector appears to provide a satisfactory method of reducing effluent gas temperature and providing a discharge at air temperature.

4—The wet collector condition with the highest performance utilized the high pressure nozzles and a high pressure pump producing 400 psi. It was found that the use of pneumatic atomizing nozzles apparently resulted in low efficiencies because their droplets were too small to have sufficient trajectory. It is apparent from this study, as well as others, that droplets in the range of 50 to 100 μ are necessary for projection across the gas stream.

5—Nozzles which utilized air and water (air-jet nozzles) can provide comparable recovery to the high pressure nozzles. The power consumption of the air-jet nozzles, however, was severalfold as compared to the high pressure hydraulic nozzles. For this reason, it is considered uneconomical to utilize air-water nozzles for collector spray production. It was also determined that the air-jet nozzle air consumption was a significant proportion of the total volume through the wet collector.

6—Wet collection produced a wet sludge which would be difficult to redisperse. The wet sludge would only have commercial value as fill for land leveling purposes unless it were dried and milled.

7—The wet collector studies also indicated that the baffle and impingement methods used did not prevent water *carry-out*. A considerable amount of water passed to the blower except when Fiberglas filters were used. Unfortunately, these proved impractical because of plugging in continued operation.

8—Nozzle orientation was not critical on performance. The most effective nozzles appeared to be those projecting across the inlet of the collector.

9—The study of the collector operated dry (as a large cyclonic unit) indicated 28% removal (mean) could be obtained.

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(4) Table II is a condensed version of the data obtained, giving only salient values. The complete Table II has been deposited as Document No. 4701 with the ADI Auxiliary Publications Project, Photoduplication Service, Library of Congress, Washington 25, D. C. A copy may be secured by citing the document number and by remitting $1.25 for photoprints or $1.25 for 35 mm microfilm. Advance payment is required and checks or money orders should be made payable to: Chief, Photoduplication Service, Library of Congress.

10—Difficulties were encountered with nozzle plugging and it was apparent that for continued operation a source of filtered water was desired. Based on the types of nozzles utilized in this study, it became apparent that the fume-laden water could not be recirculated through the unit without treatment, and fresh or well filtered water was necessary.

11—The best performance was obtained with a water : air ratio of 1 gal./130 ft.^{3} air. On full scale, this is approximately 7.7 gal. water/1000 ft.^{3} air cleaned. Water requirements, therefore, are considerably higher for 70% fume removal than for the usual desired minimum of 1 gal. water/1000 ft.^{3} air. It must be recognized, of course, that much of this water could be filtered and reused, but this involves treatment costs.

12—Tests were not sustained long enough to determine the mechanical operating performance of the unit for extended periods. Other applications have indicated that this type of device can operate for long periods without difficulty if a satisfactory water supply is available to avoid plugging of the spray nozzles.

13—Without the Fiberglas basket, the resistance of the unit could be maintained between 1.5 and 2.0 in. of water, although it must be recognized that some of the power expended in pumping water is utilized in obtaining this resistance value.

Studies with Dry Filters

Based on the authors' previous experience with filtering devices for general dust problems and the widespread use of wool fabrics in the nonferrous smelting industry, filtration through wool cloth could yield the high efficiencies desired for silica fume collection. Using wool, however, leads to temperature problems, since partially hooded electric furnace stack temperatures reach values of 350° to 400°C, and much higher, when completely hooded. In bag filter applications in the smelting industry, gases are cooled in a water spray chamber before entering the bag house. The water spray is controlled to avoid dew or condensation on the bags. With this arrangement, gases with initial temperatures of 400° to 700°C have been successfully filtered through wool cloth at efficiencies well over 99%. The major limitation to filtration through wool bags in the smelting industry has been the large size of the installation required because the filtering rate has to be maintained at 2 fpm. or less for satisfactory recovery at economical resistances.

The recent development of the reverse-jet principle for dust recovery[5] indicated that this device, which utilizes a pressed wool felt bag with a high velocity blow-back ring, has potential application in ferroalloy fume recovery. A pilot unit of this type was therefore investigated and a series of tests, which utilize 3 distinct procedures for possible application to the stack problem, were initiated.

Air Dilution

One procedure that can be employed to reduce the gas temperature is dilution with air; see Fig. 1. This requires that a much greater volume of gas and air be filtered with a comparable decrease in fume loading but with no fundamental change in the amount of material collected/unit time. The advantage of air dilution would be its simplicity; however, on an economic basis, it becomes apparent that filtration with air dilution requires installations 2 to 3 times the physical size of those used when no dilution is involved.

The dilution volume, of course, depends upon the temperatures involved. A straight linear relationship can not be assumed, however, since with the reverse-jet filter it is possible that higher volumes of air per unit area of cloth (capacity) can be obtained at reduced loading. Studies with the reverse-jet filter were made in order to determine if filtration rates as high as 10 to 15 fpm. (cfm./ft.^{2} of cloth area) could be obtained at reasonable resistances.

The test arrangement for the air dilution studies is shown in Fig. 1. A pilot model was studied. The unit had an effective filtering area of 69 ft.^{2} of cloth. Thus, at 15 cfm./ft.^{2}, it could handle 1035 cfm. A bypass damper admitted ambient air to the test duct at a point far enough from the collector inlet to permit good mixing; hence, air dilutions in various ratios could be readily obtained.

The results obtained at 3:1 dilution using wool felt in the collector are shown in Table III. The authors intended to study filter capacities (cfm./ft.^{2} of filter surface) at values of 20, 15, and 10; but, because of limited blower capacity, it was not possible to attain the highest value. Each test represents the mean of several samples taken over several hours of operation.

Table III indicates that the following conclusions may be made with regard to air dilution using a wool felt medium

[5] H. J. Hersey, Jr.: New Developments in Reverse-Jet Filters. *Quarterly* Amer. Industrial Hygiene Assn. **14**, 3 (1953).

TABLE III

Effect of Air Dilution[a] Cooling on Wool Felt Reverse-Jet Filter Performance, Fume from 50 % Ferrosilicon Furnace

Test No.	Capacity, Cfm per Sq Ft	Resistance, in. H_2O	Pct Ring Operation	Mean Inlet Temperature, °C	Loading		Pct Wt Retention
					Inlet, Grains per Cu Ft.	Effluent, Grains per 1000 Cu Ft	
1	16.1	3.4	10	45	0.042	2.2	94.8
2	9.8	2.8	10	47	0.108	4.2	96.1
3	9.9	2.8	50	54	0.192	3.4	98.2
4	11.1	3.3	25	50	0.119	2.6	98.6
5	17.1	5.8	50	48	0.204	2.4	98.7
6	16.6	5.8	30	51	0.211	2.4	98.0
7	13.2	5.7	70	51	0.181	2.2	98.8
8	12.2	5.9	50	53	0.332	2.1	99.4
9	12.6	6.0	90	50	0.628	4.7	99.3
11	12.0	6.5	40	39	0.238	3.2	98.6
12	11.1	5.1	100	52	0.357	2.7	99.2
13	7.8	3.7	90	48	0.149	6.1	95.8
14	8.9	3.8	90	48	0.171	3.0	98.1

[a] Dilution volume 3 to 1 from stack gas effluent. Each test represents 1 hr. or more sampling period downstream of filter with several upstream samples for loading. Unit was on stream over 8 day period.

and reverse-jetting on silica fume:

1—With atmospheric air dilution at 3:1 ratio, the final capacity obtained was 15 cfm./ft.^{2} at a resistance of 6.2 in. of water.

2—The efficiency was found to increase with *plugging* of the wool felt medium and ranged from 94.81 to 99.36%.

3—The air dilution method is simple but requires a unit of large size to handle the excess air volume. As shown subsequently, resistance values with air dilution are comparable to other cooling methods; hence, appreciable increased capacity cannot be obtained with lower resistance on silica fume.

Spray Cooling

A spray cooling chamber was provided as shown in Fig. 1. With this arrangement, it was possible to cool all of the gas stream or any desired portion and thus mix the remainder with the cooled portion to prevent condensation. In practice, temperature control is necessary to prevent dew or condensation from occurring at the filter surface. In this study only manual control was employed. The average water rate supplied to the chamber was 3 gal./1000 ft.^{3}. Very little of this was used in actual cooling and therefore could be recirculated. The actual amount of water to cool by evaporation was computed by heat balance as less than 0.3 gpm./1000 ft.^{3}. It was found, however, that even the coarse nozzles used for spraying were removing a significant portion of solids (approximately 15%) from the gas stream.

The conclusions obtained from the spray-cooled series on wool felt are based on the data shown in Table IV. These conclusions are as follows:

1—Efficiencies of removal of silica fume are slightly higher than in air dilution, ranging as high as 99.91%. Since the fabric had previously been plugged during the air dilution tests, this could be expected.

2—The final capacity measured with spray cooling was 9.4 cfm./ft.^{2} at a resistance of 6.8 in. of water. Spray water was supplied at 3 gal./1000 ft.^{3}, of which 90% can be recirculated after filtering the liquid to remove the solids.

TABLE IV

Effect of Water Spray Cooling [a] on Wool Felt Reverse-Jet Filter Performance, Fume from 50 % Ferrosilicon Furnace

Test No.	Capacity,[b] Cfm per Sq Ft	Filter Resistance, in. H_2O	Water Rate, Gal per 1000 Cu Ft	Mean Filter Inlet Temperature, °C	Loading		Pct Wt Retention
					Inlet, Grains per Cu Ft	Effluent, Grains per 1000 Cu Ft	
15	9.9	4.2	2.4	45	0.437	2.4	99.5
16	9.4[c]	5.2	2.5	53	0.453	3.2	99.3
17	10.9	5.6	3.7	50	0.275	2.5	99.2
18	10.7	5.6	5.1	55	0.388	2.3	99.3
19	11.8	6.5	1.2	54	0.519	6.2	98.8
20	12.8	7.0	4.8	51	0.469	1.8	99.6
21	14.3	7.5	4.6	57	0.525	0.7	99.9
22	13.8	6.8	4.3	55	0.575	0.7	99.9
24	9.7	7.2	2.5	52	0.694	0.9	99.9
25	9.5	6.9	2.9	55	0.484	0.7	99.9
26	9.6	6.9	2.4	57	0.646	0.6	99.9

[a] Each test represents 1 hr. or more sampling as in Table III. Unit was on stream over 7 day period.
[b] 100% ring operation except where noted.
[c] 50% ring operation.

3—The spray cooling chamber with coarse nozzles removed approximately 15% of the fume in the gas stream.

4—Liquid or spray cooling appears to give a more economical result, since the increase in capacity with air dilution cooling is not in proportion to the volume of air that must be handled, since only 50% increased capacity was obtained for a threefold increase in air volume.

High Temperature Medium

In order to improve performance, it was felt that, if a high temperature resistant medium with comparable performance to the wool felt could be developed for use in the reverse-jet or self-cleaning filter, it would be the ideal solution to the electric furnace fume problem.

After considerable experimentation a sandwich-type composition medium consisting of 2 layers of Orlon cloth with a layer of resin-bonded fine Fiberglas wool (feltlike) between the 2 layers of cloth was conceived, as shown in Fig. 5. After preliminary tests, this was fabricated into a bag with the Fiberglas-Orlon quilted for dimensional stability.

Initial air dilution tests were conducted with this medium, followed by continuous tests at high temperature with direct filtration. Results of these tests are shown in Tables V and VI. Actual temperatures obtained in the con-

TABLE V

Effect of Air Dilution Cooling [a] on Reverse-Jet Filter with High Temperature Medium, Fume from 50 % Ferrosilicon Furnace

Test No.	Capacity, Cfm per Sq Ft	Resistance, in. H_2O	Mean Inlet Temperature, °C	Loading		Pct Wt Retention	Remarks
				Inlet, Grains per Cu Ft	Effluent, Grains per 1000 Cu Ft		
1	21.4	4.6	5	0.00107	0.228	78.8	Atm, dust only, 0 pct ring operation
2	17.9	5.5	70	0.166	11.8	92.9	During tap
3	16.7	5.6	61	0.211	12.4	94.1	After tap
4	17.6	5.8	64	0.268	17.1	93.6	¾ hr after tap
5	15.2	6.1	54	0.293	20.7	92.9	After tap
6	15.5	6.1	42	0.236	14.9	93.7	1 hr after tap
7	16.6	6.0	50	0.178	12.8	92.8	During tap
8	13.4	6.3	33	0.430	49.2	89.6	During tap
9	13.6	6.2	38	0.348	16.6	95.7	After tap, 100 pct ring operation
10	15.4	6.0	45	0.211	15.9	92.5	During tap
11	13.3	6.0	42	0.112	9.2	93.3	After tap

[a] Approximately 2:1 dilution from stack gas effluent. <100% ring operation except where indicated in remarks. Each test represents over 1 hr. sampling downstream as in Table III. Unit was on stream over 4 day period.

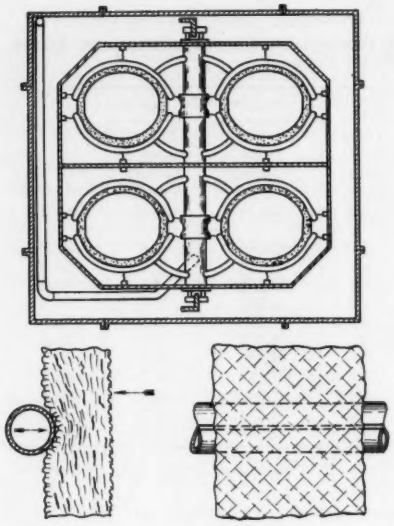

Fig. 5. High temperature-resistant medium used was sandwich-type, consisting of 2 layers of Orlon with a layer of resin-bonded fine Fiberglas (feltlike) between the 2 layers of cloth. This filter medium, cross-section and details of which are shown in the diagram of the reverse-jet filter, was fabricated into a bag with the Fiberglas-Orlon quilted for dimensional stability.

tinuous tests did not attain stack values, since apparently the heat losses from the filter and the cooling effect of the reverse-jet were present.

The high temperature medium proved satisfactory over an extended period of 648 hr. continuous duty. Failure was due to mechanical wear on the medium by blow ring rubbing. A properly fitted bag with self-adjusting blow rings which were not provided in the pilot unit would eliminate this difficulty, it is believed. The Orlon-Fiberglas combination may withstand temperatures exceeding 275°F, since the Orlon at high temperatures converts to a heat-resistant but lower strength form. The use of other abrasion and temperature-resistant fabrics is possible with the sandwich medium approach.

Conclusions based on the high temperature medium are as follows:

1—Efficiency of the high temperature medium increased in operation from 92 to 99%.

2—Capacity without any auxiliary cooling was 7.4 cfm./ft.^{2} at a resistance of 6.1 in. of water. This capacity may be improved by shaking or auxiliary sweeping or internal brushing of the bag.

3—Maximum temperature of test was 132°C, but it is believed that the medium will withstand a higher temperature without difficulty.

One item apparent in all filter tests was the importance of good furnace maintenance. When blow holes developed or improper operations were observed, filter resistance rose sharply and capacity was reduced. Improved furnace operation results in reduced loading and presumably increases filter life.

Future Developments

In regard to the dry filtration system, it was found that lower resistances could be obtained by shaking or disturbing the bag deposit, since the blow ring only loosens the layer or maintains for it a certain porosity or permeability.

At the present time, it appears possible to clean by brushing or wiping the inside of the bags simultaneouly with blow ring or reverse-jet operation. A wiping arm arrangement and vertical brushing and rotating spiral cleaning devices have been incorporated in some new units. It is believed that these developments would have potential application to this study in reducing resistance values below those obtained.

Summary and Conclusions

This paper summarizes the results of a 2-year study on methods of ferroalloy furnace fume collection at the Niagara Falls plant, Vanadium Corp. of America. A study of the performance characteristics of a wet collection unit utilizing pneumatic and high pressure fog nozzles in a cyclonic scrubber is included. An evaluation of dry collection units utilizing wool felt and a high temperature-resistant Orlon-Fiberglas medium with dilution air cooling, water spray cooling, and direct filtration with high temperature fumes is reported. A comparison of the two units, both in performance and operating requirements, is given in detail.

The results of the wet collector study indicate the best possible operating efficiency for this unit would be in the vicinity of 70% with a resistance to flow or overall pressure loss of approximately 2 in. of water. Experiments utilizing a Fiberglas basket packed with varying grades of coarse Fiberglas as a trap for *carry-out* (moisture and fume) and equipped with washdown sprays were not successful and indicated that it was not possible to maintain efficiencies above 70% during sustained operation

(Continued on page 48)

TABLE VI

Performance of High Temperature Medium[a] in Reverse-Jet Filter, Fume from 50% Ferrosilicon Furnace

Test No.	Capacity, Cfm per Sq Ft	Resistance, in. H_2O	Mean Inlet Temperature, °C	Loading		Pct Wt Retention	Remarks
				Inlet, Grains per Cu Ft	Effluent, Grains per 1000 Cu Ft		
12	11.0	6.0	95	1.25	28.3	97.7	Before tap, <100 pct ring operation
13	9.8	6.1	86	0.378	18.0	95.2	During tap, <100 pct ring operation
14	11.3	6.2	95	1.18	26.2	97.8	After tap
15	10.5	6.2	85	0.640	18.0	97.2	Before tap
16	9.9	6.2	91	0.476	17.2	96.4	During tap
17	9.0	6.2	78	1.04	15.8	98.5	After tap
18	12.7	6.3	113	1.16	19.2	98.3	After tap, <100 pct ring operation
19	11.8	6.0	110	0.510	14.1	97.2	Before tap
20	11.7	6.0	107	0.092	9.5	89.7	During tap, <100 pct ring operation
21	9.5	6.2	98	0.354	9.8	97.7	After tap, <100 pct ring operation
22	8.5	6.2	103	0.614	13.1	97.9	During tap, <100 pct ring operation
23	7.8	6.1	95	1.29	13.4	99.0	After tap
24	7.1	6.0	103	1.12	10.6	99.1	Before tap
25	7.0	6.4	94	0.810	12.0	98.5	After tap
26	7.4	6.1	80	0.832	7.2	99.1	Through tap, <100 pct ring operation
27	8.9	6.0	96	0.701	8.9	98.7	Through tap

[a] Each test represents over 1 hr. sampling downstream as in Table III. Data above was taken over 6 day period but filter continued in operation with sampling for 648 hr. before tests ended due to motor failure.

The Control of Gob Pile Fires*

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During the last quarter of a century there has been a growing awareness on the part of communities that there is a penalty that has to be paid when industry settles in their midst. Basically, industry treats raw material producing goods and in so doing is left with waste products. Such waste products may be solid, liquid or gaseous, and the disposal of them presents a problem of ever-increasing difficulty. Recognition by the public that the disposal of industrial wastes was a matter that would have to be tackled resolutely only came by degrees, and, consequently, in the past industry gave little thought to the problem.

As pointed out by Pendray[1], it is public opinion that determines the pace of industry's attack on the disposal of its wastes. In considering industry, a distinction must be made between enterprises that have a choice or selection of location and site, and those which are controlled by the location of raw products such as quarrying, sand and gravel pits and coal mining. Industries engaged in such pursuits are definitely restricted to the location of the deposits being worked. The wastes associated with such activities were considered a nuisance whose cost of disposal yielded no return on expenditure and, therefore, a minimum of effort and cost was the approved procedure.

As Dr. Richard D. Hoak[2] has said, "Through the ages, man has always had the habit of befouling his own nest." In the past that has been true of the coal industry.

Where coal is mined by the "room and pillar" system, the disposal of waste has varied with the detailed operations. In the days of the "pick" miner when coal was hewn out by hand, it was first *forked* over with forks having their tines on approximately 1¼-in. centers. The undersize, although a great deal of it was good coal, was discarded and thrown back into the old workings. Thus it was not brought outside and placed on the refuse or *gob* piles. Similarly, a great deal of the roof rock was discarded inside the mine. In *longwall mining*, a type of mining little used in the USA, most of the waste is employed in the building of pack walls and, therefore is not sent out for disposal on the surface. In fact, in some operations, material from the surface (chiefly sand and crushed refuse) is introduced into the mine to augment the supply of *pack* material.

With the advent of machine mining, *i.e.*, cutting machines, electric drills and electrified haulage in the mine and screening plants on the outside, the amount of refuse to be disposed increased, although at many operations, some degree of the old quality was retained by penalizing the coal loader for loading dirty coal. At this period the refuse discarded averaged approximately 8% of the tonnage produced.

Then came the mechanical loader and full seam mining inside the mine and modern coal washing and preparation plants on the surface. The miner was no longer an individual working independently and being paid for the number of tons of clean coal he loaded. Rather he was a member of a crew or team operating equipment in a cycle and sending out a raw product that had to be cleaned and prepared for the market by modern coal cleaning machinery. No longer was a penalty imposed for the loading of dirty coal as the mechanical loader loaded all material that lay before it. The efficiency of the coal cleaning equipment was relied upon to produce a fuel that was of satisfactory quality to meet the demands of the market. Naturally, the amount of refuse it was necessary to discard increased tremendously. At many operations at the present time the quantity of refuse discarded amounts to 33% of the tonnage produced. Naturally, during these changes in methods of mining, the quality of refuse in percentage of combustible varied as widely as the quantity, so that the presence of material prone to fire spontaneously was different in various sections of the pile or piles.

These phases of mining practice spread over decades and encountered various degrees of public reaction. For many years the burning refuse or *gob* piles that were to be seen at practically all bituminous coal mines were considered both by management and the public as an inevitable accompaniment to the operation. Little or no study was made to ascertain if the disagreeable conditions could be alleviated, and some designers of refuse handling equipment actually made allowance for the shrinkage of a pile brought about by the burning of the combustible accompanying the discarded refuse. Efforts were even made to increase the shrinkage by laying down the material in such a manner that combustion would be encouraged.

In the last 15 years, however, there has been a growing insistence that greater effort be made to dispose of trade wastes in a manner that will alleviate the pollution problem experienced in rivers and skies of industrial areas. Allegheny County, Pa., in which Pittsburgh is situated, became the leader in this movement. In addition to bringing domestic and commercial heating plants under control, the regulatory officials enlisted the aid of the two dominant industries in the area, the steel and coal industries. Both of them agreed to underwrite certain research projects in an attempt to find answers to the particularly difficult atmosphere pollution problems associated with their operations. The coal industry's problem was the control of gob pile fires. Briefly, it covered 2 phases:

1. To quench burning piles and have them remain extinguished.
2. To construct piles so that they will not ignite in the future.

The studies were underwritten by the Western Pennsylvania Coal Operators Association and carried out by the Mellon Institute of Industrial Research. The actual research project was under the guidance of Dr. William L. Nelson, to whom the author of this paper is deeply indebted for a great deal of the data that are incorporated in this presentation. In conducting this investigation, basic studies were carried out on the ingredients that comprise the pile, the proportions of those ingredients, size of the various particles and the nature of their distribution as they are laid down by the equipment delivering them.

In regard to combustible material contained in the discarded refuse, it is comprised of coal of various forms—sand, shale, clay, gypsum, particles of iron carbonate and iron sulphide (pyrite), as well as other impurities. Great fluctuations in the proportions and physical conditions of the materials that comprise the refuse are encountered. Kennedy[3]

* Presented at the 48th Annual Meeting of the Air Pollution Control Association at Detroit, Michigan, May 23-26, 1955.

(1) Pendray & Co., New York, N. Y.

(2) Richard D. Hoak, Mellon Institute of Industrial Research, Pittsburgh, Pa.

(3) G. W. Kennedy, Rochester-Pittsburgh Coal Co., Indiana, Pa.

has presented examples indicative of the fluctuations in make-up that are given below in Table I.

From the foregoing figures it will be seen that approximately ½ of the discarded material is combustible, that is, composed of carbonaceous matter and sulphur. Inasmuch as the major part of the refuse comes from wet cleaning plants, it is delivered to the refuse pile in a wet condition. Thus, there is presented a mixture of materials that are conducive of spontaneous heating.

Essentially, this spontaneous heating of coal is an oxidation process involving combustible material and the associated pyrite (FeS_2) with its sulphur content. The moisture too contributes to the self-heating process. The atmospheric oxidation of the pyrite is an important factor in the spontaneous combustion process in 2 ways:

1. Directly because the reaction is strongly exothermic.
2. Indirectly by the oxidizing reaction as the area of coal surface exposed to oxidation is increased.

The more finely-disbursed the pyrite in the refuse, the more effective it is in developing self-heating.

The dry oxidation of the pyrite proceeds as follows:

$$Fe\,S_2 + 3\,O_2 \rightarrow Fe\,SO_4 + SO_2$$

With moisture present, both on the particle and as water vapor in the air, conditions are created that favor the more strongly exothermic wet reaction, with the formation of sulphuric acid as follows:

$$2\,Fe\,S_2 + 2\,H_2O + 7O_2 \rightarrow 2\,Fe\,SO_4 + 2\,H_2SO_4$$

With the development of heat in or on the pile from the foregoing reactions, the rate of heat dissipation will determine the extent of spontaneous heating and the ultimate ignition of the gob pile.

Thus, there is an optimum ventilation rate that is conducive to ignition. It is dependent in the degree of compactness and segregation that is encountered in the pile as it is laid down. Piles that favor such conditions as loose compaction and severe segregation are those formed by installations using aerial tramways for gob disposal. Also, the careless dumping of trucks which deposit highly-segregated refuse at locations at the edge of the pile selected at the whim of the truck driver.

In further consideration of the role of pyrite in gob pile fires, it may be of interest to note the manner of their presence. It may appear as crystalline "Brassy pyrite" or "fools' gold" which is noticeably visible as yellow or gold colored nodules. It may also occur as flakes and lenses, or again as fine particles disseminated through the coal substance. Larger concretions are known as "sulphur balls". FeS_2 may also be encountered in a gray form that is known as marcasite. Pyrite also occurs in the *partings* present in most coal seams as fine particles of black amorphous material.

In addition to these natural materials contained in the refuse piles, unless strict supervision is maintained, there will be encountered a quantity of trash, wood, pit props, crank case oil, oily rags and waste that greatly increase the fire hazard, and, as if to augment the hazard, these inflammable materials are generally found at the toe of the pile amongst the highly segregated lumps of refuse high in combustible material.

One other factor, not fully considered, is the inevitable effect of erosion on deposited materials. Erosion gulleys are cut into the pile and form thereby a serrated edge that greatly increases the exposed fresh surface to oxidation and encourages rapid air currents through "chimney effect" up the face of the pile.

With all these influences serving to encourage the ignition of refuse piles, one basic principle for the control of gob pile fires becomes clear. All oxidation should be kept to an absolute minimum. In practice this can be brought about by compaction of the discarded materials and smothering the pile with finely-divided material, such as clay or sludge, from the settling basins of the cleaning plants.

Having stated the basic factors that must be met if any measure of success is to be attained, inevitable compromises must be made in order to satisfy local conditions. Topography is a dominating factor. In the prairie states with level terrain, laying down the refuse is a comparatively simple operation. Segregation can be kept to a minimum and drainage from the adjacent land areas rarely presents a problem.

The general procedure calls for spreading the refuse in a layer over the surface of the pile. Whether the layering process is carried out immediately upon discharge of the material or allowed to stand in heaps of individual truck loads is dependent on the characteristics of the refuse. Certain clays and shales spall and disintegrate into small flaky particles when exposed to the weather. If such is the case, a *weathering* period, varying from weeks to months, will not only aid in attaining a greater density when the material is ultimately spread and compacted, but will allow the pyritic content to be exposed to the oxidizing process while in the free ventilation of the atmosphere. Where refuse has little or no *weathering* characteristics, spreading the material in layers as it is received from the wet refuse bin of the preparation plant is the common practice. Layer disposal, however, despite its advantages does not assure freedom from spontaneous ignition. Sometimes the layers are laid down so thick that the compacting equipment (bull dozers, rollers, trucks, *etc.*) can only compress a comparatively thin surface crust of the material. Underneath the refuse may be only lightly compacted, and the voids present may be great enough to allow spontaneous heating to take place.

As a general rule, the efforts toward compaction have been confined to the top of the pile. Actually, the edges or sides of the pile, where some segregation is unavoidable and where wind and air currents have a tendency to sweep up the face, are more prone to ignite. Therefore, greater efforts should be made toward the compression of the edges of the pile. There are a number of ways of accomplishing this task. Where the edges can be *feathered* out to a gentle slope of 50% or less (27° or less), the bull-dozer can be employed to drive over the surface and compact it. Such a slope is convenient for the application of an apron of clay for sealing.

Where the slope of the face of the pile is left to follow the natural angle of repose, specially-designed rubber-tired mounted rollers carrying steel rail as ballast are attached to the bull-dozer and operated over the sloping face of the pile. Compaction is thus brought about for at least 10 ft. down the slope of the pile from the top edge. The unrestricted upsweep of wind over a steep face greatly accelerates burning. Therefore, in

TABLE I
Analysis of Refuse

	Equipment	Size	Ash %	Combustible %	Sul. % (Det. Sep.)
Mine No. 1	Bradford Breaker	10″ x 1″	52.60	47.40	11.8
	Cleaning Cone	1″ x $\frac{3}{16}$″	50.60	49.40	10.60
	Deister Tables	$\frac{3}{16}$″ x 0″	48.60	51.40	12.7
	Total Refuse	10″ x 0″	51.40	48.60	11.40
Mine No. 2	Refuse	2″ x 0″	50.0	50.0	5.00
Mine No. 3	Refuse	2″ x 0″	60.3	39.7	7.15

order to break this sustained upward sweep, a terraced face has been adopted at some properties. Such horizontal terraces also permit the compaction of the face of the pile to be carried out at different levels.

In hilly terrain, the methods must be modified to conform with the restrictions of the site. If the discarded refuse is to be deposited around the contour of the hillside, it may be feasible to dig a trench approximately 30 ft. wide and 15 ft. deep at the contour level and throw the spoil to the downhill side. This creates a space into which the refuse can be discharged by truck. The supervised operation of the trucks over the refuse as it is unloaded effectually compacts it, and both sides are sealed between the earth of the excavated hillside and the spoil on the downhill side. Thus only one face (approximately 30 ft. by 15 ft.) is exposed to oxidation, and that face is continually being covered with fresh material. When the trench is filled, a second can be superimposed on it by repeating the hillside excavation on a suitable contour above that used originally. This method of disposal, which has been highly successful, is an ingenious adaption of good principles to the restrictions of the site.

In many cases the space available for waste disposal consists of a valley with or without a considerable watershed behind it. Provision is usually made to handle the *run off* either through a culvert placed in the bottom of the pile and protected from drainage, heat and breakage, or by turning the drainage away from the vicinity of the pile. Then both sides of the valley are excavated on similar contours and the spoil "*borrowed*" for the formation of a sealing dam across the valley entrance at some convenient location. The basin thus created provides the space for the discarded refuse. The surface of the layers is kept level, both sides and one end are compacted against the cuts in the sides of the valley, and the spoil dam, respectively. The thickness of the layer gradually tapers out to a *feather edge* as it is carried up the valley. A supervised pattern of truck travel over the surface of the layer insures compaction, especially if augmented through the use of bull-dozers and rollers.

In the case of *terraced* piles previously described, there is the inevitable increase in surface exposure due to erosion. Even if a sealing apron of clay is used, unless the pattern of the apron is properly designed, there will be a tendency for the apron to be cut by gulleys.

Dr. Nelson[4] in his research on this subject, has developed methods that will not only greatly reduce erosion, but will hold the moisture in V trenches in the clay spoil. There is promise that such soil could be planted and some vegetal cover be devoloped to improve the appearance of the generally unsightly gob piles. If such a scheme could be successfully developed, it would certainly result in improved public relations. It does require, however, further experimentation in regard to types of plants, etc. that would be most adaptable. Such work is being carried out with tests on various grasses, legumes and trees. Studies of the acidity of the piles and the rate of leaching of various types of refuse material have been considered.

The foregoing examples of constructing gob piles in a manner that will inhibit combustion were for the most part developed for application to new piles that were to be laid down. Where piles are actively burning, other methods have been employed first to quench the fire and then permit fresh refuse to be deposited on the same site.

Local situations often present difficulties that call for unique solutions. It should be remembered that where a pile has been burning for years, much of the calcined material (known locally as *red dog*) is fused into large masses that do not readily break up. Other material, although burned, has maintained its discrete particles. Where the material is fused together, there is little justification economically in attempting to blast it apart and level it. However, if the tops of the piles can be levelled and compacted to facilitate the movement of refuse hauling trucks, a procedure of *encroachment* can be practiced whereby the refuse is dumped down the internal faces of a series of basins or holes that are ringed around with a compacted level of refuse permitting the trucks to travel around the periphery. Although the faces of the basins may be actively burning, the continual deposition of fresh refuse around the surface tends to smother the flame and gradually fills in the hole. Compaction of the top edge of the internal face of the basin, through the use of rubber-tired compaction rollers, assists in the reduction of active combustion. The continual operation of the loaded trucks across the filled-in portion and around the dumping edge effectively compacts the pile. When the basin is completely filled, the surface provides an expanse over which the trucks and bull-dozers may roam as desired by the drivers. In all this, however, a pattern of truck travel to yield maximum compaction must be adopted and maintained. Spreading out of the refuse with bull-dozers and scrapers until the piles have a gently-rounded contour permits the use of equipment that compacts and smothers the active burning. Care must be exercised, however, in closing in on active areas because of possible voids that may exist below the surface. Such unexpected situations may be dangerous to both man and equipment.

A rather interesting method of approach in quenching an actively-burning pile was used in the midwest. A stream or jet of water at high pressure knocked down the burning debris and placed it so that the bull-dozer could spread the material out in a layer of uniform thickness. Such a treatment presupposes an ample water supply (or reuse of the water) for hydraulicing and comparatively level terrain to simplify the disposal of the solids.

Having described certain methods of approach toward the problem of controlling the fires encountered in refuse piles at coal properties, it may be profitable at this point to consider what success has been attained. What good has been accomplished? How permanent is it? What will happen when the mine is worked out and supervision is withdrawn?

Some of these questions can only be answered in the process of time. The initial control of refuse fires has been rather successful. However, little would have been done without the spur of enacted legislation. The law in force in Allegheny County, Pa. was sagacious in adopting a cooperative research effort between industry and the regulatory bodies, with an adequate period of time in which to carry out investigations. This cooperative attitude on the part of industry was accelerated by growing awareness of all that an atmospheric pollution problem exists in many areas. This resulted in the passage of smoke abatement ordinances. Unfortunately, legislation, while it expresses the people's will, does not always provide the correct solution for the problem. Often they are superficially conceived because emotional evaluation of the effects of pollution may take precedence over a diagnosis of the problem based on a study of the engineering and economic aspects and the geographical and meteorological factors involved. Such a danger was avoided through the Mellon research sponsored by the Western Pennsylvania Coal Operators Association.

One final point must be touched upon. The meteorological conditions

(Continued on page 51)

[4] W. L. Nelson, Mellon Institute of Industrial Research, Pittsburgh, Pa.

Field Evaluation of Wet Fiber Filters for Treatment of Air Contaminants*

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Gas absorption equipment utilizing beds of wetted fibers has been shown[4] to have important advantages over conventional methods for the concentration and recovery of valuable gases and similar equipment may be utilized to treat waste gases of little or no commercial value for the control of atmospheric pollution. Investigations[1,3] have demonstrated that large diameter fibers can be employed effectively for gas absorption when formed into batts 3-8 in. thick and placed in horizontal-flow, wet cell washer cabinets similar to those commonly used for the humidification of industrial and commercial air supplies. Laboratory studies of the absorption efficiency of wet fiber cells and fiber droplet eliminators showed recoveries of approximately 99.9% for HF and greater than 90% recovery of sub-μ sized chemical fumes and mists.

Fibers

Fibers were found to be superior to the more usual types of packings in relation to the amount of surface available for absorption/unit volume and in addition, high porosity of the fiber beds favored low-resistance gas flow. See Table I. Concurrent spraying permitted higher gas velocities than are practical with countercurrent operation and reduced channeling resulted in better wetting of the packing. (Small losses in driving force, because of concurrent spraying, were compensated by more uniform wetting and higher gas velocities.) Also shown in Table I are porosity and relative efficiency of several packing materials. From this it may be seen that 78 μ diameter fibers were many times more effective than Berl saddles or Raschig rings for absorption and that for equal efficiencies the total weight of a fiber bed may be as little as 1/150th that of ½-in. Berl saddles; thereby permitting smaller, lighter and less expensive housings or towers.

Although much of the developmental work on the properties of fiber packings was done with glass fibers, the excellent chemical resistance and packing characteristics of synthetic plastic fibers recommended their use for many applications. Plastic fibers also have excellent resistance to erosion and breakage and because of their low specific gravity (generally less than 2.0) they provide a large surface area/lb. of packing. A large selection of synthetic fibers of many sizes, chemical compositions, shapes and lengths is now available.

Scrubbing Liquid

A minimum number of stages are required when the scrubbing liquid rapidly neutralizes or reacts with the gas or vapor to be removed from the gas stream. In areas where water resources are limited, or where industrial waste disposal facilities are restricted, the use of chemical absorbents (rather than water alone) is advantageous and the small quantities of chemicals consumed by the low gas concentrations involved in air pollution problems makes their use desirable in most cases. In addition, neutralizing solutions were important factors in reducing or eliminating corrosion of equipment.

Insoluble Particulates in the Gas Stream

When gas streams contained large quantities of insoluble materials such as mineral dusts, gas scrubbing cells and mist eliminator pads rapidly became plugged and air-flow resistance increased. Previous investigations[1,2] showed that a wetted impingement type collector called a Neva-clog screen was capable of removing up to 85% of mineral particles (such as silica or talc dusts) and, in addition, had considerable value as a gas absorption stage. For example, when a Neva-clog screen was wetted with 4.4 gal. of water/min./ft.^{2}, removal efficiency for HF was 92%[2]. On the basis of these and similar tests this wetted impingement device was found to be effective as a first gas scrubbing stage when treating gases contaminated with mineral dusts of comparatively large size. Very small particles such as atmospheric dust are generally not a problem since they tend to penetrate wet scrubbing cells and dry eliminator filters and cause little or no plugging difficulties.

Construction of Absorption Equipment

A typical arrangement of wet and dry elements is illustrated in Fig. 1. The initial stages are absorption cells; the first, an impingement screen and then 2 of large diam. fibers. Three absorption stages are shown but the actual number

[2] First, M. W., Moschella, R., Silverman, L., and Berly, E. M., *Ind. Eng. Chem.*, **43**, 1363 (1951).

TABLE I

Physical Characteristics and Height of a Transfer Unit of Some Gas Absorption Packings

Packing Material	Weight, Lbs./Ft.^{3}	Surface Area Ft.^{2}/Ft.^{3} of Packing	Porosity, Fraction Voids	Approximate Cost of Packing			Height of a Transfer Unit, Ft.
				Per Cubic Foot	Per Lb.	Per Sq. Ft. of Surface	
78-μ Diam. Plastic Fibers	6	912	0.95	$ 6.20	$1.00	$0.007	0.14[a]
Berl Saddles ½ in. Porcelain	45	141	0.68	26.50	0.24	0.190	0.81[b]
1 in. Porcelain Berl Saddles	42	79	0.69	9.95	0.59	0.130	0.85[b]
1 in. Porcelain Raschig Rings	45	58	0.68	4.25	0.10	0.070	1.00[b]

[a] Based on Gas Rate of 480 fpm. and Liquid Rate of 1680 lb./hr./ft.^{2}.
[b] Based on Gas Rate of 400 fpm. and Liquid Rate of 1500 lb./hr./ft.^{2}.
Data of Fellinger, as presented by Sherwood & Pigford, "Absorption & Extraction," McGraw Hill Book Co., New York City, 1953.

* Presented at the 48th Annual Meeting of the Air Pollution Control Association at Detroit, Michigan, May 23-26, 1955.

[1] Berly, E. M., First, M. W., Silverman, L. *Ind. Eng. Chem.*, **46**, 1769 (1954).

[3] First, M. W., *et al.*, U.S.A.E.C., Report No. NYO 1581, Waste Disposal, Harvard School of Public Health, Boston (1952).

[4] Williams, G. C., Akell, R. B. and Talbott, C. P., *Chem. Eng. Prog.*, **43**, 585, (1947).

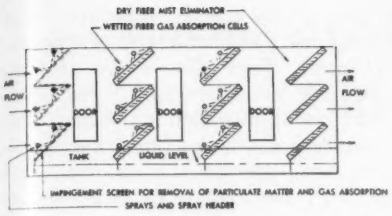

Fig. 1. A typical gas absorber utilizing an impingement screen to remove particulate materials and wetted fibers for gas absorption.

may vary from 1 to 3 depending on the specific problem. Fibers and impingement screen are wetted at the rate of 3.5 gpm./ft.² of filter surface with 2 low pressure (5-10 psi) flooding nozzles/ 20 x 20 in. cell placed a few inches upstream of the face. Scrubbing liquid is recirculated from the sump by means of a suitable pump. The final stage is a deep-bed, fiber filter for mist elimination. In practice, carry-over of fine droplets from the wet stages made it necessary at all times to include a dry, fine-fiber filter as a final stage when high efficiency collection was required even though no mist or fume was present in the entering gas stream.

Resistance

Satisfactory air and gas flow rates ranged from 100 to 225 cfm./ft.² of face area and collector resistance was proportional to flow rate. Resistance increased in proportion to packing density of the fibers and depth of the filter and decreased as the diameter of the fibers became larger. High efficiency scrubbers containing several absorption stages had resistances of 6 in. of water or less when operated at flow rates of 215 cfm./ft.².

Field Installations

Industrial gas scrubbers were installed to control the discharge to the atmosphere of hydrogen fluoride (gas and mist), hydrochloric acid and acetic acid-acetic anhydride. Results of field tests and a description of scrubber and operating conditions are summarized in Table II, while manufacturing processes, design criteria and analysis of test results are detailed below.

Installation 1

Glass electronic tubes were being cleaned with an HF solution in large enclosed, automatic machines and the fumes exhausted to the outdoors without treatment. Concentration of HF in the exhaust air was sufficient to etch windows of adjoining houses and ruin the finish of automobiles in the vicinity. Spotty, pit-like damage to automobile paints suggested droplets of hydrofluoric acid while the generalized nature of the window etching indicated the presence of gas also.

A gas absorption scrubber, Fig. 2, was installed to handle part of the exhaust from the washing machine hoods. It contained 3 wet gas absorption stages (Neva-clog screen and 2 banks of 4-in. thick, rubber-bonded Dynel fibers) and a 4-in. deep dry filter (also of rubber-bonded Dynel) to serve as a droplet eliminator. The scrubbing liquor was 5% Na_2CO_3 solution circulated through each wet stage at a rate of 3.8 gpm./ft.² of face area. Low pressure (8-10 psi), hollow cone spray nozzles were used to flood the upstream face of the gas scrubbing cells and Neva-clog screen. The unit was so constructed that cells were easily removable in order to observe results with 1, 2 and 3 wet scrubbing stages. Results are listed in Table II (Tests 1a, 1b and 1c). They show that wet Neva-clog screen and dry filter alone removed 76% of HF present in the inlet gases. The addition of 1 and then 2, 4-in. deep Dynel wet cells increased efficiency to 90.5% and 99.4%, respectively. Results for the 1 and 2 wet stage gas absorbers (Tests 1a and 1b) were somewhat lower than those obtained in the laboratory with HF using similar equipment. Examination of the scrubber cabinet at the conclusion of these tests indicated possible leakage around the first 2 wet stages due to faulty gaskets. Efficiency of the unit with 3 wet stages was in reasonably good agreement with laboratory data, however.

Because the quantities of HF in the hood exhaust gases were found to be very small, it was concluded that a scrubber containing 1 wet Dynel cell and 1 dry Dynel filter would be adequate for the control of HF gas and acid droplets emitted from this operation.

Installation 2

A cotton acetylating machine reeled cloth through a series of tanks containing hot glacial acetic acid and acetic anhydride and then between rollers (after each dip) to squeeze out excess solvent. As a final operation, acetylated cloth passed between heated rollers for drying. The machinery was enclosed as tightly as possible to avoid loss of vapor and maintained under a slight negative pressure to prevent escape of fumes into the workroom.

A gas absorber was installed to remedy a neighborhood nuisance from the stack fumes. It contained 2 stages of wetted glass cells (240 μ diam. fibers), a bent plate eliminator (to remove coarse droplet carry-over) and a final dry stage of fine glass fibers for small droplet removal. Hollow cone flooding nozzles at

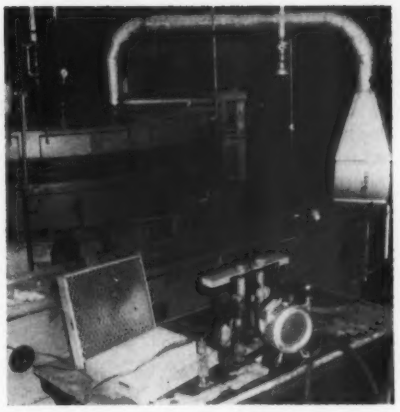

Fig. 2. Gas absorber for HF.

8.5 psi. provided approximately 3.3 gpm. of liquid/ft.² on each wet stage. The scrubbing liquor, a 5% solution of technical grade Na_2CO_3, was recirculated and freshened with saturated solution as required. At the request of the purchaser, considerable excess capacity was provided and the air flow rate was 75 ft./min. through wet cells and dry filters, somewhat lower than usual. The quantity of vapors escaping from the acetylation process was underestimated in the original design, and it was found that the capacity of the liquid sump was adequate for short periods of operation only. This suggested the use of automatic controls for maintaining scrubbing liquor strength.

Two efficiency tests on this gas absorber are listed in Table II. The first represents conditions at the start of a run when hoods and enclosing walls (as well as the machinery itself) were cool enough to condense large volumes of vapor before escape to the exhaust system. The second tests were made about 6 hr. later when, because of heating of the equipment, *etc.*, the quantity of vapors escaping the process had increased more than 3-fold. (Intermediate samples, not given, indicated a progressively increasing rate of loss of vapor from the process). In spite of the very large quantities of vapor to be scrubbed (*i.e.*, 1.25% by vol. during the last test), collection efficiency remained well over 99%. The concentration of glacial acetic acid and acetic anhydride leaving the gas scrubber when the inlet concentration was the highest was 0.25 mg./m.³. This concentration (equivalent to approximately 100 ppm. as acetic acid) was not considered excessive for discharge from a stack. Neighborhood complaints were not received nor were any difficulties in this respect anticipated.

Installation 3

The products of combustion from the

burning of silicon tetrachloride (to form a very pure silica) included silicon dioxide (a solid white fume), hydrogen chloride and undetermined quantities of a number of oxychlorides and their hydrates. Unburned silicon tetrachloride, which decomposes in a humid atmosphere to form hydrochloric and silicic acids, was also present.

The gas absorber employed for this operation was identical with the one used for the absorption of HF (described above) except that a spray nozzle was placed in the inlet duct to precool the gases (entering at approximately 350°F) before they reached the scrubber proper so as to prevent destruction of thermoplastic corrosion-proof coatings on cabinet and cell frames.

Tests were made (1) by recirculating 5% sodium carbonate scrubbing solution, and (2) using all fresh water on each wet stage and no recirculation of the sump liquor. Results of both operating conditions are shown in Table II, Test 3. Although inlet gas concentrations (reported as HCl) are exceptionally high (*i.e.*, up to 2% by volume), scrubber efficiency was excellent with both scrubbing liquids. The use of all fresh water would eliminate the cost of neutralizing chemicals, but costs of fresh water plus enlarged waste disposal facilities might make the use of a sodium carbonate scrubbing liquor more economical.

Although absorption was satisfactory and the acid concentration in the effluent gases was low enough for safe disposal by stack emission, little or no decrease in the quantity of fine silica fume leaving the furnace was effected by the Nevaclog screen or by the wet and dry filters. Cooling and humidifying the air stream as it passed through the absorber appeared, in some manner, to greatly intensify the opacity of the silica fume so that the resulting stack plume was quite visible. Although no health hazard was judged to be present (nor was the silica dust objectionable because of its odor or soiling characteristics), plant personnel felt it might be desirable to further improve the appearance of the stack effluent by removing a large percentage of the solids. The temperature of the gases leaving the unit was reduced to approximately 75°F and a cloth collector for removing silica fume was considered practical if further cleaning was required.

Summary and Conclusions

Experience with 3 wetted fiber gas absorbers has demonstrated the practicality of this type of apparatus for atmospheric pollution control of industrial effluents. Tests have shown that the high efficiencies obtained in the laboratory can be duplicated in industrial practice. Although none of these installations has been operated, as yet, for a sufficiently long period to make observations on corrosion resistance of great value, the information that is available is uniformly favorable. Use of mildly alkaline sodium carbonate scrubbing solutions is undoubtedly an important factor in prolonging the useful life of the metals and corrosion-resistant plastic coatings used in these installations. Neither glass nor Dynel fibers have shown signs of erosion, corrosion or embrittlement in the period they have been in service.

These field trials have shown that high efficiency absorption may be obtained with high or low inlet gas concentrations and at resistances ranging from 0.8 to 4.0 in. of water gage (depending on air flow rate and number and composition of the cleaning stages). The necessary maintenance and service procedures have proved acceptable to plant personnel both with respect to frequency and amount of time required.

TABLE II

Field Performance of Multiple-Stage, Wet-Fiber Gas Absorbers

Test No.	Material to be removed	Absorber elements, given in order they contact air stream	Air Flow cfm./ft.^{2}	Air Flow Resistance in. W. G.	Liquid flow gpm./ft.^{2}	Scrubbing liquor	Concentration mg./m.^{3} inlet	Concentration mg./m.^{3} outlet	Cleaning Efficiency %
1a	HF (gas & mist)	(1) Nevaclog screen (2) 79μ Dynel dry pad, 2 in. thick	216	2.3	3.8	5% Soln. Na_2CO_3	.00470	.00112	76.0
1b	HF (gas & mist)	(1) Nevaclog screen (2) 79μ Dynel wet cell, 4 in. thick (3) 29μ Dynel dry pad, 2 in. thick	190	3.1	3.8	5% Soln. Na_2CO_3	.00484	.00046	90.5
1c	HF (gas & mist)	(1) Neva-clog screen (2) 79μ Dynel wet cell 4 in. thick (3) 79μ Dynel wet cell 4 in. thick (4) 29μ Dynel dry pad, 2 in. thick	160	4.5	3.8	5% Soln. Na_2CO_3	.00158	.000011	99.4
2	acetic acid & acetic anhydride	(1) 200μ glass wet cell, 4 in. thick (2) 200μ glass wet cell, 4 in. thick (3) 100μ glass dry pad, 2 in. thick	75	0.8	3.3	5% Soln. Na_2CO_3	9.51 32.00	.041 .253	99.5 99.2
3	hydrochloric acid & silicon tetrachloride	(1) 50μ curly glass fiber wet cell, 4 in. thick (2) 50μ curly glass fiber wet cell, 4 in. thick (3) 50μ curly glass fiber dry pad, 2 in. thick	216[a]	4.0	3.8	H_2O 5% Soln. Na_2CO_3	3.15 30.00	.0025 .054	99.9 99.8

[a] Gas temperature: 340°F entering, 75°F leaving.

Engine Air Flow Measurements as an Aid to Automotive Exhaust Analysis

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Ford Motor Company
Dearborn, Michigan

This instrument fulfills a need for an air flow meter to be used in conjunction with a portable infrared exhaust gas analyzer[1] to provide a quantitative measure of the rate of emission of exhaust components from vehicles on road test. The instrument was to measure the air consumed by a standard automotive engine during normal road operation. The instrument was further required to impose no abnormal operating conditions on the vehicle. It was to be rugged, portable, simple to use, small in size, and to fit all popular make post-war automobiles. An accuracy within 10% of indicated air flow was felt to be satisfactory.

Previous experience in the field of air-flow measurement suggested the possibility of developing a viscous type air flow element to replace the standard automotive air cleaner. This type of flow element had many apparent advantages and only a few disadvantages.

A major advantage was compactness, since no surge tank is necessary in most applications. It appeared that the flow element could be installed in a standard air cleaner shroud and that adapters could be used to fit a great many cars.

The limitations, although few in number, should not be overlooked. The pressure drop across the flow element would necessarily be small in order to be within the normal air cleaner pressure drop at equivalent flow rates. Measurement of this small differential pressure is difficult in a moving vehicle.

Since the instrument appeared to be feasible for the purpose intended, a series of such meters were constructed. This paper outlines the theory, development and application of these instruments.

Flow Meter Theory

The principle of the viscous flow meter is relatively simple. For a fluid flowing in a pipe of known cross-sectional area, the quantity flowing may be calculated if the average velocity is known. Assuming no change in fluid density, the quantity is:

$$Q = AV \qquad (1)$$

where: Q = quantity of fluid flowing
A = cross-sectional area
V = average velocity

In a simple orifice, the velocity is proportional to the square root of the pressure difference. In a viscous flow meter, this is not the case. For laminar flow in non-circular tubes, the pressure drop is predicted from:

$$\Delta P = \frac{K}{N_R} \cdot \frac{\rho V^2}{2g} \cdot \frac{l}{D} \qquad (2)$$

where: K = constant depending on units and geometry
N_R = Reynolds number
ρ = fluid density
g = acceleration of gravity
l = length of tube
D = hydraulic diameter
ΔP = pressure drop

It is generally accepted that laminar flow will exist if the Reynolds number is below 2000. The Reynolds number is defined as:

$$N_R = \frac{DV\rho}{\mu} \qquad (3)$$

where: μ = absolute viscosity

Substituting equation (3) in equation (2)

$$\Delta P = \frac{K\mu}{DV\rho} \cdot \frac{\rho V^2}{2g} \cdot \frac{l}{D} \qquad (4)$$

which becomes

$$\Delta P = \frac{K\mu Vl}{2gD^2} \qquad (5)$$

Solving for velocity, V and substituting in equation (1)

$$Q = \frac{\Delta P 2g A D^2}{\mu K l} \qquad (6)$$

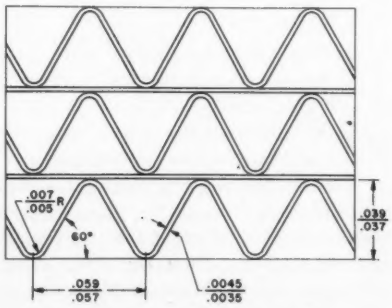

Fig. 1. Section through matrix

For a fluid of given viscosity and density, for a pipe of known geometry, and for conditions of laminar flow, the quantity of fluid flowing is directly proportional to the pressure drop.

Flow Element Geometry

Laminar flow may be created by reducing velocity, reducing hydraulic diameter, or increasing viscosity. In designing a flow element for vehicle use, 2 additional factors must be considered; namely, pressure drop limitations and flow element size.

In order to minimize the effect of the flow meter on carburetion, a serious attempt was made to have the flow meter operate within the same pressure drop range as the standard air cleaner. In addition, the flow meter was designed so that air entered the carburetor in essentially the same path as that provided by the standard oil bath air cleaner. Investigation of air cleaner performance indicated that 1 in. of water pressure drop for every 100 ft.³/min. of engine air flow was typical.

The triangular section matrix appeared desirable for the flow element. The triangular section is formed by winding a crimped aluminum or steel sheet sandwiched between 2 flat sections. Thus a matrix element is formed in which all of the passages have the same geometry. The passages are equilateral triangles 0.038 in. in height. Aluminum 0.004 in. thick was used for all flow elements. Fig. 1 is a drawing of a section through the matrix.

The length of the flow element determines the pressure drop for a given quantity of flowing fluid. Engine compartment dimensions necessitated a relatively short flow path. An experimental matrix element was wound in the form of a disk 10 in. in diam. and 3 in. air path length. To check experimentally the pressure drop and flow rate, this disk-shaped matrix was fabricated into a flow element. Fig. 2 is a photograph of this original flow element, and Fig. 3 illustrates a cross-section through a diameter. Tests with this prototype unit indicated that an area of approximately 27 in.² of matrix would be needed to produce 1 in. of water pressure drop at 100 ft.³/min. of air flow.

[1] Neerman, J. C., Parsons, J. L., and Bryan, F. R., "A Continuous Flow Method of Determining Unburned Fuel in Automotive Exhaust." *J. of APCA* (this issue) p. 38.

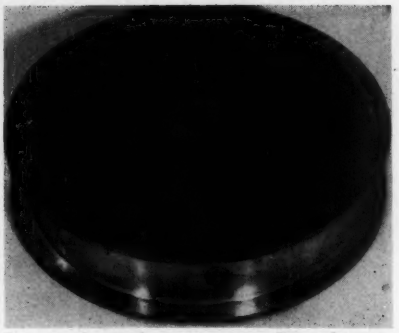

Fig. 2. Original matrix type flow element.

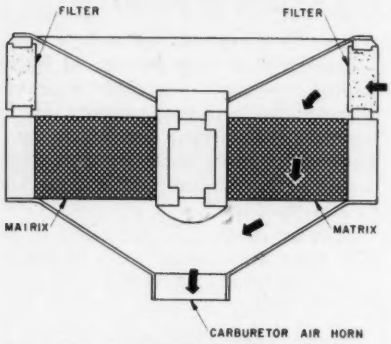

Fig. 3. Section through No. 1 air flow meter.

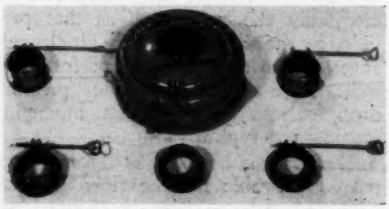

Fig. 4. Enclosed flow element and adapters for various engines.

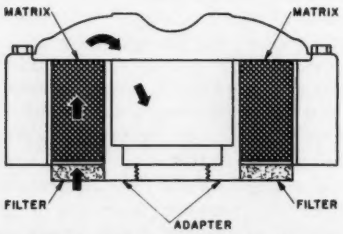

Fig. 5. Section through No. 3 air flow meter.

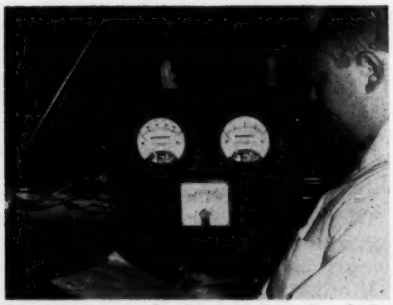

Fig. 6. Indicating head mounted inside vehicle.

On the basis of these experiments, a series of flow elements were fabricated. One of these units was designed for universal use. A center section was removable and a number of adapters provided so that the flow element would fit a variety of vehicles. Fig. 4 is a photograph of this flow element, and Fig. 5 is a cross-section through a diameter. The matrix itself was fabricated to fit within the standard air cleaner housing of a Ford 6-cylinder engine.

The Indicating Head

The recent availability of relatively rugged gages for differential pressures below 1 in. of water simplified the difficult problem of measuring low pressures in a moving vehicle.

Two Magnehelic gages and a temperature indicator were mounted in a small sheet metal cabinet provided with hooks and rubber cushions for mounting on the door window of the vehicle being tested. A photograph of this indicating head is shown in Fig. 6.

The 2 pressure gages were selected to cover the range of air flows expected with the largest scale factor available. One gage had a range of 0-1 in. of water and the other a range of 0-4 in. of water It was intended that the 0-1 in. of water gage would be used at low flow rates from idle to 30 or 50 miles/hr., above which the 4-in. gage would be practical.

After fabrication, the first flow element was calibrated on a flow stand using the Magnehelic gages as indicators. Fig. 7 is one of the early calibration curves which has remained essentially unchanged.

The instrument was then installed in a vehicle and some preliminary road air flow measurements were made. Fig. 8 shows the under hood installation of the first instrument in a 1955 Lincoln, and Fig. 9 depicts the complete installation. Fig. 10 shows some preliminary road data.

Preliminary tests showed the following deficiencies requiring correction:

1. Differential pressure taps were subject to velocity pressures due to car motion.
2. The Magnehelic gages were much too sensitive to accelerations in the plane of the gage.
3. The Magnehelic gages were subjected to excessive vibration.

Experimentation revealed that a flush pressure tap within the flow element shroud was the least sensitive to external air velocity. To check the effect of air flowing over the flow element shroud, the test car was driven at 70 miles/hr. At this speed, the transmission was placed in neutral and the engine stopped. When the differential pressure gage remained on zero, the effect of air velocity was assumed to be negligible.

The Magnehelic gages were mounted in the longitudinal plane of the vehicle to reduce the effects from car accelerations and decelerations. However, accurate air flow measurements are limited to straight sections of roadway.

Shock mounting the gages in foam rubber eliminated vibration difficulties.

An indicating head was also built using a Wallace and Tiernan 0-10 in. of water differential pressure gage. This unit was less subject to acceleration effects but gave a reduced scale factor at low air flow rates.

Calibration of the Instruments

The air flow instruments were calibrated against rounded edge flow nozzles with known coefficients. For each instrument, several calibrations were made over the complete range of the instruments. The calibration procedure was to measure the pressure drop and flow rate with the instrument in series with the calibrated nozzle.

It was recognized that any factor which affected the viscosity of the flowing fluid would alter the calibration. There are 2 things which alter the viscosity of air:

1. Air Temperature
2. Water Vapor

The variation of air viscosity with temperature is accurately known for all possible temperatures which would be encountered. Part of the measuring procedure is to record the air temperature at the entrance to the flow element. As the temperature increases, the viscosity of air increases. As the viscosity increases, the pressure drop also increases for the same quantity of air flowing. As a result, for equivalent pressure differentials, the quantity of air flowing decreases as the temperature increases. Fig. 11 provides temperature correction factors to be applied above 70°F, the calibration temperature, due to the change in air viscosity. The temperature correction amounts to about 0.15%/1°F change in temperature.

The viscosity correction due to water vapor in air is not so easily determined. The data in the literature are conflicting[2]. However, it appears that the correction is probably negligible in the range of accuracy required for the present problem.

Viscosity corrections due to barometric

[2] "International Critical Tables," Vol. V, p. 6, McGraw-Hill Book Company, Inc., New York 1929.

pressure changes are entirely negligible.

The density of air at the ambient temperature and pressure of the flow element inlet is used to convert volume flow to mass flow.

The Effect of Pulsations on Meter Accuracy

Much work has been done in England on the use of viscous flow meters for the measurement of pulsating flow[3]. This work was stimulated by the fact that a well damped manometer indicates the arithmetric average of the pressure pulsations; and the average flow can be computed if the flow meter is linear. The orifice fails in this respect because a root mean square average is necessary to measure average flow. In the course of their investigations, viscous flow meters were coupled as close as physically possible to the inlet manifold of a single cylinder engine. Under these severe conditions, accurate average flow rates could be obtained only by manometer damping which in itself must be viscous. When the following precautions were observed, accurate average flows could be attained:

1. Viscous damping at pressure taps with felt pads or oil-filled manometer leads.
2. Small leads of relatively soft material.
3. A manometer whose natural frequency is removed from the engine pulsation frequency.
4. Reynolds numbers below 1000.

The instruments described in this paper utilize these design features.

It must be noted that meters of this type are many times referred to as linear flow meters. This is not strictly the case. Although the basic relationships for flow within a small tube indicate linear relationship, the physical embodiment of any real flow meter generally introduces entrance and exit disturbances which force the calibration curve to depart from a linear function, and pulsations can then cause errors due to improper averaging of the pressure.

The flow meters built for this application operate at average Reynolds numbers between 100 and 400, lower by a factor of 2 than the indicated safe limit. The low Reynolds numbers are used to insure that laminar flow is present even at the peaks of any pulsations that might exist. Since the engines under survey are for the most part 8 cylinder engines, the pulsation problem is minimized. During idle, critical flow exists in the throttle body and any pulsations present are not transmitted to the flow element.

In general, the problem of pulsation has not been considered serious for the problem at hand, due to the low Reynolds numbers used and the small average amplitude of the pulsations encountered.

The Effect of Dirt on Calibration

Due to the size of the passages in the flow element, these instruments are subject to errors due to an accumulation of dirt in the flow element. The effect of dirt is a higher pressure drop for the same air flow rate when compared with a clean element. The only apparent solution to this problem is a filter ahead of the flow element and periodic cleaning. The flow element must be kept free of oil or other substances which might act as a collector for dust or dirt.

Field Use of the Flow Meters

These flow meters have been field tested over a period of several weeks, during which they appeared to be reliable, rugged, and simple to use. At the beginning of the test period, the flow elements were carefully cleaned and the meters calibrated. During 4 wks. of field use, the meters were not cleaned. After their return to the laboratory, a second calibration was performed. The second calibration showed only negligible differences from the first. Within the accuracy of measurement, the second calibration was identical to the first.

Field test experience suggested that a more convenient indicating head could be constructed. It would contain a 0-1 in. of water Magnehelic gage for idle air flow measurements and a 0-10 in. of water Wallace and Tiernan instrument for road load measurements. In this manner, the best advantage could be taken of the sensitivity of the Magehelic gage at idle and the stability of the Wallace and Tiernan gage under road load conditions. Future instruments will incorporate this refinement.

Conclusions

Engine intake air flow data from an automobile under actual road operating conditions may be obtained using the viscous flow meter described.

Although the initial intent was to produce an instrument of 10% accuracy, the present instrument appears to be considerably better, perhaps near 4 or 5%,

(Continued on page 49)

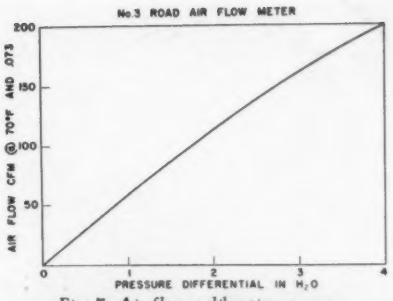

Fig. 7. Air flow calibration curve.

Fig. 8. Installed air flow element.

Fig. 9. Car equipped with flow element and indicating head.

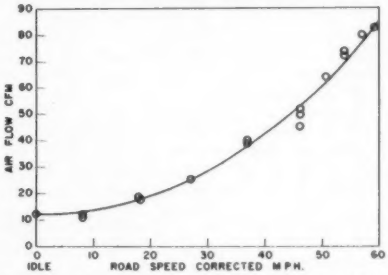

Fig. 10. Air Flow vs. road speed — 1955 Lincoln.

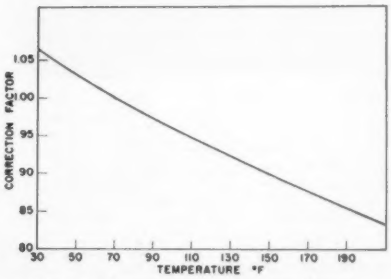

Fig. 11. Temperature correction factor.

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[3] Kastner, L. J., and Williams, T. J., "Pulsating Flow Measurement by Viscous Meters, with Particular Reference to the Air Supply of Internal-Combustion Engines." Paper presented at the General Meeting of the Institution of Mechanical Engineers, London, February 18, 1955. Summary in *The Chartered Mech. Eng.*, **2**, 102-3 (February 1955).

A Continous Flow Method of Determining Unburned Fuel in Automotive Exhaust

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Dearborn, Michigan

For the past few years, attention has been directed toward the detailed composition of automotive exhaust gas for the dual purposes of increasing combustion efficiency and guarding against excessive air pollution[1-8]. In addition to the usually recognized major combustion products, emphasis is now being placed on the more elusive minor constituents which are becoming recognized as important indices of both engine combustion processes[9] and smog forming reactions[10].

One class of exhaust constituents, readily measurable and significant to engine engineers, is the hydrocarbon series representative of unburned gasoline. This series of compounds includes hydrocarbons containing predominantly C-H bonding , and containing 3 or more carbon atoms to the molecule. A quantitative index of this unburned fuel is used in the development of carburetion and combustion control devices on engines[4,7,9], and in air pollution survey work involving automobiles[1,8].

This paper describes instrumentation, procedures, and resulting quantitative determinations of C_3 and higher fuel components on both engine dynamometer and vehicle road tests. Instrument response time being within 2 seconds has allowed the measurement of transitional as well as steady state operating conditions. The limit of detection is approximately 0.01 mole % of hydrocarbon. Concentrations ranging from 0.05 to 1.0 mole % are effectively accommodated.

Apparatus

The analyzer employed in this work consists of an interference filter photometer[11] designed to measure the 3.43 μ absorption band due to paraffinic CH_2 and CH_3 groups which produce several overlapping absorptions in this wavelength region[12-16].

The assembled photometer is shown in Fig. 1. The essential internal components consist of a heated ribbon source, a 20 in. sample cell, the interference filter[17], and a compensated thermopile detector. Visible in the figure are the electrically operated optical shutter, a pump to provide continuous flow through the cell, and valves to select either exhaust sample or reference air for measurement.

Control circuits are housed separately from the photometer to allow remote operation. The control box (Fig. 2) contains the signal-detecting circuits together with photometer shutter and valve controls. The detecting circuit is of the null indicating type[18] with potentio-

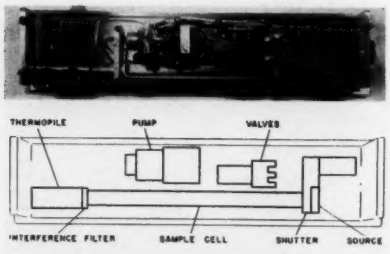

Fig. 1. Photometer assembly incorporating motor-operated pump, valves and optical shutter. Built to order upon request.

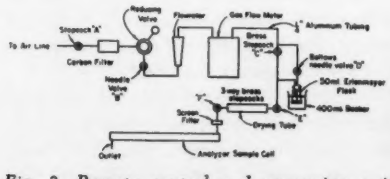

Fig. 2. Remote control and measuring unit together with recorder.

Fig. 3. Equipment layout for dynamic calibration of analysis.

[1] Magill, Paul L., Hutchison, D. H., and Stormes, J. M., "Hydrocarbon Constituents of Automobile Exhaust Gases," *Proceedings Second National Air Pollution Symposium*, pp. 70-83, Stanford Research Institute, Stanford, Calif., 1952.

[2] Walker, J. K., and O'Hara, C. L., "Analysis of Automobile Exhaust Gases by Mass Spectrometry," presented at Southern California Air Pollution Foundation Meeting, Pasadena, Calif., August 18, 1954.

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[4] Chandler, J. M., Cannon, W. A., Neerman, J. C., and Rudolph, R., "Engine Variables and Their Effects on Exhaust Gas Composition," *J. of APCA*, **5**, 65 (August 1955).

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[14] Francis, S. A., "Absolute Intensities of Characteristics Infrared Absorption Bands of Aliphatic Hydrocarbons," *J. Chem. Phys.*, **18**, 861 (1950).

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[17] Mooney, C. F., and Turner, A. F., "Infrared Transmitting Interference Filters," Paper No. 10. Fort Belvoir Infrared Colloquium, February 10, 1955, Conference on Infrared Optical Materials, Filters, and Films.

[18] Coggeshall, N. D., and Saier, E. L., *J. Appl. Phys.*, **17**, 450 (1946).

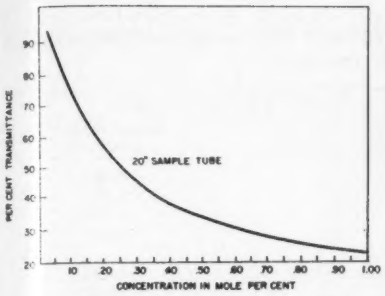

Fig. 4. Calibration curve; percent transmittance vs. concentration of nhexane.

meter dial calibrated to read directly in percent transmittance for manual null balancing. Provision is also made for attaching a self balancing recorder for measurement of transient conditions such as deceleration. A 3-position, ganged, selector switch provides proper photometer shutter and valve positions for zero adjustment, 100 % adjustment, or percent transmittance measurement.

An interconnecting electrical cable allows complete operation of the photometer from the control box location which may be several feet from the photometer in certain mobile installations. For mobile operation, power for the equipment is supplied from a storage battery and converter.

Calibration

The analyzer is initially calibrated by introducing measured hydrocarbon-air blends[19] into the sample cell on a continuous flow basis. A diagram of the calibration equipment is shown in Fig. 3. Since a pure hydrocarbon is more easily handled than a mixture such as gasoline, a representative pure paraffinic hydrocarbon was selected for the calibration. *n*Hexane was used since its absorbtivity closely approximates that of typical gasolines. A range of hydrocarbon concentrations in air is provided by adjusting the valves to divert various fractions of the total air flow into the flask containing *n*hexane.

[19] Gisclard, J. B., "Simple Device for Preparing Vapor-Air Mixtures," *Ind. Eng. Chem.* Anal. Edit., **15**, 582 (1943).

TABLE I

Infrared Filter Photometer Analyses of Exhaust from an Engine on Engine Dynamometer

Test Condition	Air/Fuel Ratio	rpm.	C_{3+} Hydrocarbons in Mole %
Cruise	....	1006	0.066
Idle	....	431	0.10
Simulated Deceleration	....	1004	1.05
Idle:			
(Rich)	4.36	454	0.79
	8.95	454	0.26
	10.95	452	0.15
(Std.)	13.85	458	0.075
	15.80	454	0.21
(Lean)	16.95	460	0.35

Fig. 5. Road test installation showing photometer unit located in car trunk. Sampling line and air condenser are shown attached to tailpipe.

The hydrocarbon concentration is determined by measuring the total air flow with a gas flowmeter and the weight of *n*hexane evaporated during the same period of continuous operation. The mole percent of *n*hexane can then be plotted directly versus percent transmittance as in Fig. 4.

Operating Procedure

Samples are obtained from the engine exhaust system either at a point a few inches upstream of the muffler on dynamometer-mounted engines, or from within the tailpipe on vehicle-mounted engines. The analyzer can be mounted on a cart adjacent to the engine or vehicle for stationary tests. For road operation the photometer is mounted in the trunk compartment so that the sampling line from the tailpipe is short. The control unit in this case is located inside the car for convenience.

Since the high percentage of water vapor in engine exhaust absorbs 3.43 μ radiation appreciably, the bulk of the water is removed from the sample prior to analysis. Either Drierite or a simple air condenser serves to remove water sufficiently to prevent serious interference with the hydrocarbon measurement.

Fig. 6. Road test installation showing control unit, recorder, and power supply located in car interior.

Before making determinations the analyzer source is turned on for several minutes to allow the instrument to reach a stable operating temperature. Subsequently, the steps in operating the analyzer correspond to the typical procedure for photometry. Zero and 100 % transmittance adjustments are made, the sample is introduced, and sample transmittance is read from either the potentiometer dial or recorder. The calibration curve (Fig. 4) provides the corresponding concentration of unburned fuel.

Analytical Results

Unburned Fuel in Mole Percent (Dry basis)

A very useful application is the determination of the relationships between engine operating variables and unburned fuel. Using an engine dynamometer, a series of steady state test conditions is established and corresponding hydrocarbon analyses obtained. Individual measurements are made within 1 min. and repeatability of readings is within ± 10% of the amount present. Typical averaged results are shown in Table I.

The equipment is readily adaptable to moving vehicle operation by locating the photometer in the trunk for convenient sampling (Fig. 5), and the con-

TABLE II

Exhaust Analyses from Tailpipe of a Moving Car

Driving Condition	Approx. mph.	rpm.	Mole % C_{3+} Hydrocarbons — Individual Readings					Avgs
Idle	..	450	0.070	0.069	0.075	0.079	0.069	0.072
Cruise	10	490	0.073	0.062	0.062	0.060	0.062	0.064
Cruise	20	970	0.048	0.045	0.044	0.043	0.047	0.045
Cruise	30	1400	0.047	0.045	0.043	0.036	0.038	0.042
Cruise	40	2065	0.035	0.039	0.036	0.036	0.038	0.037
Cruise	50	2490	0.043	0.033	0.039	0.036	0.034	0.037
Cruise	60	2945	0.026	0.024	0.027	0.029	.....	0.027
Deceleration (Maximum concentration after closing throttle at 40 mph.)	..	....	0.58	0.62	0.75	0.72	0.60	0.65

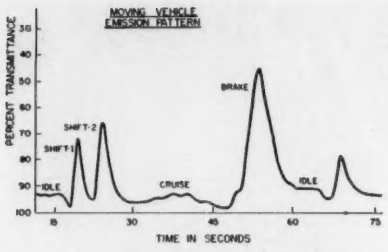

Fig. 7. Section of record representative of typical road operation.

trol unit and recorder inside the car (Fig. 6). For vehicle tests a tailpipe sampling probe reaches about 3 ft. upstream from the end of the tailpipe. This manner of sampling is essential because of the possibility of air dilution near the end of the tailpipe. Results of a series of road tests are shown in Table II. These consist of individual and averaged hydrocarbon concentrations obtained by manual null balancing.

Using the recorder, percent transmittance can be plotted versus time to provide a record of hydrocarbon emission during vehicle operation. A typical recording appears in Fig. 7, illustrating emission configurations related to idle, cruise, acceleration and deceleration conditions.

In order to assess the reliability of the interference filter photometer as a hydrocarbon detector, analytical comparisons were obtained by means of another nondispersive infrared analyzer calibrated on the basis of *n*hexane absorption. Both infrared analyzers were mounted in the rear seat of a car and were connected so as to sample dried exhaust simultaneously from a single sampling line. The comparative results, given in Table III, show that determinations obtained from the 2 instruments are almost identical.

Also, since many previous determinations of hydrocarbons in automotive exhaust have been obtained by mass spectrometry[1-4], it was considered of importance to compare infrared and mass spectrometric results. Samples were taken from an engine on dynamometer test, where it was convenient to collect simultaneous flask samples for mass spectrometry. Comparative data are shown in Table IV. Filter photometer results correlate well with mass spectrometer determinations of "C_3 and higher hydrocarbons." Although absorption at 3.43 μ due to C_1 and C_2 hydrocarbons is very slight, it is likely that photometer results are increased to some extent by relatively large amounts of C_1 and C_2 molecules produced under operating conditions such as deceleration or rich idle.

[1-4] See footnote 1-4, page 38.

TABLE III

Comparative Road Test Results from Infrared Filter Photometer and Liston-Becker Non-Dispersive Analyzer

Driving Condition	Mole % C_3+ Hydrocarbons	
	Interference Filter Analyzer	Liston-Becker Analyzer
Idle	0.081	0.080
	0.091	0.081
	0.092	0.090
	0.097	0.095
Cruising 30 mph.	0.043	0.045
	0.036	0.035
	0.040	0.038
	0.036	0.037
Deceleration From 40 mph. (Maximum hydrocarbon concentration)	0.31	0.31
	0.33	0.33

Unburned Fuel in Weight Per Unit Time

The emission rate of hydrocarbon in terms of mass/unit time *i.e.*, lb./hr. is a better criterion of air pollution than concentration alone. Emission rate can be computed as the product of the concentration of hydrocarbon in the exhaust multiplied by the exhaust flow rate. The hydrocarbon analyzer and a portable air flow meter[20] were used together to measure the emission of hydrocarbons from a moving car under various operating conditions.

The air flow meter consists of a viscous flow element which replaces the engine air cleaner, and a differential pressure indicator mounted inside the car. The flow element consists of an air cleaner housing fitted with a crimped aluminum matrix offering a low but measurable pressure drop. Pressure indicators are Magnehelic gages calibrated to cover differential pressures from 0-3 in. of water, and corresponding flow rates of 0-170 cfm. At a road speed of 40 mph., for example, the air flow is about 40 cfm. and the resulting differential pressure is about 0.5 in. of water. A thermocouple measures the inlet air temperature.

Assuming a typical air/fuel weight ratio of 12/1 and a typical fuel composition of 14% by weight hydrogen, it can be shown that 0.97 lb. of dried exhaust are produced for each 1.00 lb. of intake air. From calculations based on analyses of exhaust at widely varying operating conditions (idle, cruise, and deceleration) it was determined that the density of dried exhaust is the same, within ± 2%, as the density of air (at the same temperature and pressure). Therefore, 0.97 multiplied by the intake air volume flow and the ratio of the absolute temperatures of the analyzer

(Continued on page 47)

[20] Millar, G. H., "Engine Air Flow Measurements as an Aid to Automotive Exhaust Analysis." *J. of APCA* (this issue) p. 35.

TABLE IV

Comparative Infrared Filter Photometer and Mass Spectrometer Analyses of Exhaust from an Engine on Engine Dynamometer

Test Condition	Air/Fuel Ratio	rpm.	Mole % Hydrocarbons (Dry Basis)				
			Infrared Photometer	Mass Spectrometer			
			C_3+H.C.[a]	C_3+H.C.[a]	CH_4	C_2H_2	C_2H_4
Cruise	....	1006	0.066	0.065	0.034	0.015	0.043
				0.061	0.034	0.013	0.046
Idle	....	431	0.10	0.086	0.065	0.022	0.060
				0.075	0.064	0.023	0.060
Simulated Deceleration	....	1004	1.05	0.85	0.16	0.10	0.38
				0.91	0.15	0.10	0.33
Idle: (Rich)	4.36	454	0.79	0.60	1.32	0.91	0.47
	8.95	454	0.26	0.20	1.00	0.89	0.25
	10.95	452	0.15	0.11	0.47	0.35	0.14
(Std.)	13.85	458	0.075	0.066	0.049	0.013	0.060
	15.80	454	0.21	0.25	0.003	0.00	0.055
(Lean)	16.95	460	0.35	0.37	0.001	0.00	0.062

[a] C_3 + H.C. = C_3 and higher hydrocarbons.
Note: Duplicate MS analyses were made on separate exhaust samples.

Operating Characteristics and Economics of a 100 Ft.^{3}/Day Incinerator for Radioactive Wastes*

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Lemont, Ill.

In common with most industries, atomic energy is faced with the problem of waste disposal. The more ordinary problems of waste disposal are present, but they are overshadowed by the necessity of handling radio-activity. Radioactivity cannot be destroyed by any process except the natural decay of the various species. The usual waste treatment, therefore, consists either of diluting the waste with sufficient inert material so that the discharge concentrations are below established tolerances, or of concentrating the activity into an economically storeable volume. Discharge tolerances are so low that dilution is often not practical.

Solid, liquid, and gaseous wastes are produced and must be handled. This paper discusses one approach to one part of the solids-handling problem.

The cheapest and most popular method of solid waste disposal is the landfill. This method has the disadvantages of:

1. Putting the activity in a place where it may be subject to leaching by ground water.
2. Allowing the possibility of scavenging by small animals.
3. More or less permanently denying access to land areas.

In highly-populated areas it is sometimes impossible or at least unwise to use the landfill disposal method. Therefore, methods were sought to allow the reduction in volume of solid wastes.

It has been determined that the dry active wastes collected at Argonne National Laboratory are about 50-80% (by volume) combustible. This represents a sizable volume and a portion of the problem vulnerable to attack. After considering a number of processes the decision was made to study incineration. An incinerator capable of handling 100 ft.^{3} of waste/day was designed and built at Argonne National Laboratory. The unit is shown in Fig. 1.

This unit was put on routine daily operation in July 1951. It was the first full-scale unit to be installed as a production unit for the combustion of radioactive wastes. It was operated for about 2 yr., and performance and economic data were obtained.

Process Description

The incinerator equipment consists of a Type 330 stainless steel incinerator body in which the material is burned in the presence of excess air; a Schreier-Bartolucci vane plate washer in which large particles of fly ash are removed; and a secondary scrubbing unit consisting of a Pease-Anthony Venturi and a Peabody scrubber in which the gas-borne radioactivity is normally reduced to within tolerance. Final clean-up is accomplished by an AEC filter. The ash resulting from combustion falls through a grate system and settles through water located in the cone in the base of the furnace into a canvas bag filter inside of a stainless steel drum. The bag and its contents are removed from the system, dewatered, and then stored.

That segregated combustible radioactive waste which is below 50 mr./hr. is routinely brought to the incinerator area in 1-ft.^{3} fiber drums, loaded onto stainless steel pallets, and hoisted by a crane to the loading platform. The drums are charged into the furnace through electrically-interlocked double doors on the charging chute which prevent blow-back of radioactive ash or fumes from the furnace. The drums build up on the grates of the furnace and are ignited by gas burners located around the circumference of the incinerator. Air is supplied both below and above the grates in order to insure complete combustion. The air supply is drawn from outside the building to eliminate the possibility of radioactive smoke being dissipated through the building in the event of a puff resulting from momentarily accelerated combustion.

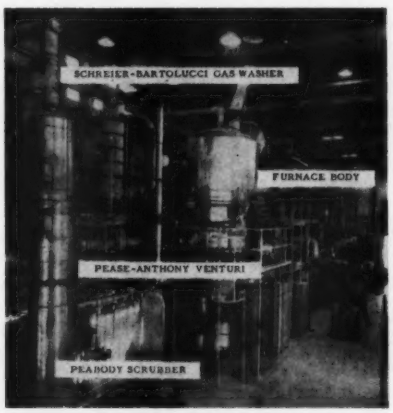

Fig. 1. Incinerator.

As combustion proceeds, the ashes drop through the grates into the cone-shaped bottom of the furnace where they are collected in water. The ashes settle through the water and through a plug valve into a water-filled drum containing a bag filter located beneath the furnace. When a bag is filled with ash, the valve is closed and the drum and bag filter are replaced.

The products of combustion pass upward through the furnace and out through a horizontal gas duct located near the top of the combustion chamber. Most of the heat of combustion is dissipated by generation of steam in a water jacket surrounding the upper part of the combustion chamber. This heat is carried to the fan loft where it is transferred to the atmosphere in standard forced-draft unit heaters. Gases leaving the furnace pass first through a Schreier-Bartolucci vane plate tower. Here the larger pieces of fly ash are scrubbed out from the gases with a water stream which also serves to cool the gases. Water for this scrubbing operation is pumped from the bottom of the ash barrel to the top of the Schreier-Bartolucci tower and returned from the bottom of this tower to the lower portion of the combustion chamber. This scrubbing solution is maintained alkaline through the addition of sodium hydroxide.

The gases, now freed of the larger particles of fly ash, are passed to a Pease-Anthony Venturi scrubber where the high velocity gas stream is used to disintegrate a water stream which is admitted at the throat of the Venturi. This intimate mixture of air and water is admitted tangentially to the bottom of the Peabody scrubber. In this disengaging section, the gas and the droplets of water containing a large fraction of the smaller particles of dust are separated. The gas flows upward through the Pea-

* Presented at the 48th Annual Meeting of the Air Pollution Control Association at Detroit, Michigan, May 23-26, 1955.

body tower passing through fine holes in scrubbing plates where the gas is brought into further intimate contact with the scrubbing solution. In the upper portion of the Peabody tower the gas and water are separated by a mechanical baffle system. The gases then flow past electrical heaters located above the scrubbing tower. Sufficient heat is added by these heaters to vaporize any fine mist particles which are still present in the gas and to raise the gas temperature several degrees above the dew point, thus preventing condensation in the remainder of the system. Like the scrubbing solutions in the Schreier-Bartolucci tower, the liquid in the Peabody scrubber is also recirculated. This scrubbing liquid, which is maintained basic with sodium hydroxide, is pumped from the bottom of the Peabody tower and returned to the top of the same tower or through a heat exchanger to the Pease-Anthony Venturi.

The general flow of solution in the scrubbing train is from the end of the gas scrubbing train toward the furnace. In the furnace and the Schreier-Bartolucci tower, water is evaporated from the scrubbing solution. This water is condensed in the succeeding cooler portions of the system. The heat of condensation is removed in a water-cooled heat exchanger. The result is that water tends to accumulate in the cooler portions of the system and is evaporated from the furnace and primary scrubber (Schreier-Bartolucci), but automatic controls maintain constant liquid levels throughout the system.

The preceding treatment may be enough in most cases of operation to reduce the radioactivity to a permissible discharge level. However, as a final safeguard, the gases are passed through a filter of the AEC type. This filter is capable of removing radioactive particles to well within the maximum tolerance levels specified by this laboratory's Radiological Safety Section (2×10^3 beta disint/(min.)—($m.^3$) and 70 alpha disint/(min.)—($m.^3$)). When replacement is necessary, the loaded filter is burned in the furnace. From the filter, the gases are drawn through a positive displacement blower which moves the gas stream on to the discharge stack on the roof.

A by-pass is provided in the gas duct system at a point just preceding the Schreier-Bartolucci tower. This line provides a pressure relief system in the event a surge within the furnace occurs from an unusually rapid period of combustion. Such a surge of gases can be vented directly to the roof, preventing disruption of operation of the equipment.

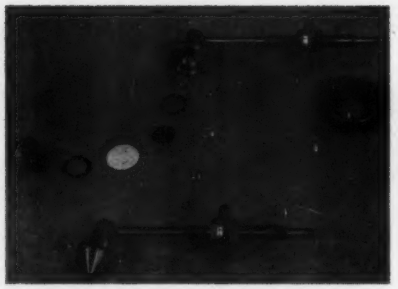

Fig. 2. Gas filter assembly.

The principal collection point for particulate and activity is the ash barrel below the combustion chamber, hence all scrubbing solution flow is directed to this locality. The gases with entrained particulates are borne outward from the furnace through the scrubbing train. The scrub liquids flow in a general countercurrent manner from the scrubbing train inward towards the furnace and return the particulates to the ash barrel.

Sampling

With the recirculating scrub solution system employed in this installation, it is not possible to determine the amount of activity or particulate removed by each piece of scrubbing equipment through sampling of the scrub solution. Rather, it is necessary to rely upon samples taken from the gas stream.

Sampling of the gas stream to determine the efficiency of each piece of equipment is carried out in 2 ways. The first method is based on the total amount of activity entering and leaving each unit. The second method is based on the total weight of particulate entering and leaving a unit. Experimental results, have shown that these 2 methods produce nearly identical results, at least in the less-than-2 μ particle size range.

Two types of sampling equipment are used, both employing the principle of filtering the gas stream to remove the particulate. The gases in the ducts are sampled by means of the sample head shown in Fig. 2. This device is placed inside the gas duct facing upstream, and by means of vacuum, the sample is drawn through the filter paper in the sample head. The sample flow rate is measured by a gas rotameter and the volume calculated from the length of time that the sample was taken.

One advantage of placing the sample head in the gas duct is the prevention of condensation in the sampler. Condensation can cause 2 problems, (1) moisture weakens the filter paper and, (2) condensation formed on the walls of the sample tube would tend to collect particulate and thereby invalidate the results. Another advantage is that if there are any sharp bends in the sample probe, some of the heavier particulate may be desposited on the walls of the sample tube. This can be circumvented by placing the sample collection device within the duct so that the sample is collected before any bends in the tube occur. For sampling gas which is less than 200°F., the filter media used is Whatman 44 paper. The gas streams having a temperature greater than 200°F. are sampled with a special fiber glass filter, AAA superfine. This filter medium has an average pore size of 0.6 μ.

After the sample has been taken, the filter is removed and the radioactive count is determined. For weight determinations, the sample medium is dried and weighed prior to and following the sampling. Both weight efficiencies and activity efficiencies can be determined on each sample. Efficiencies are based on the influent and effluent concentrations of the particulate in the gas at each unit of the scrubbing train.

The monitoring sampling device, used to determine the amount of particulate radioactivity being discharged to the atmosphere, is a modified vacuum cleaner which draws the gas through a filter paper (Hollingsworth and Voss Number H-70). This monitoring, based on radioactive counting of particulate, helps to insure safe operation of the incinerator with respect to the total amount of radioactivity discharged to the atmosphere.

Experimental Program

The overall objectives of the incinerator program were:

1. The incinerator was to serve as a production unit.
2. The Argonne incinerator was essentially a prototype unit since it was the first production sized unit to be operated successfully on a routine basis. Therefore, it was necessary to perform experimental work that would provide sufficient data to be the basis for design of future incinerators.
3. As with any new process, it was necessary to perform sufficient experimentation to determine the most economical operation.

Removal of Radioactivity

The amount of activity or solids retained by the furnace itself was determined by use of spiked charges. This was determined on a radioactivity basis. These data are expressed as a decontamination factor (DF), which is the ratio of the influent feed radioactivity concentration to the effluent gas radioactivity concentration. The average de-

contamination achieved in the furnace body itself was a factor of about 200.

As it was not feasible to sample the gas stream between the Pease-Anthony Venturi scrubber and the Peabody scrubber, the effect of the Pease-Anthony Venturi scrubber on radioactivity removal efficiency was determined around the Pease-Anthony Venturi-Peabody scrubber couple. A maximum DF of 50 was obtained.

The effect of the water to gas ratio in the Venturi can be seen in Fig. 3. The water rate was varied between 2.0 and 13.0 gal./min. and the gas flow from the incinerator was varied between 285 and 425 scfm. This resulted in a water to gas ratio varying between 4.7 and 45.6 gal./min./1000 scfm. The efficiency reaches a maximum of about 93% at about 20 gal./min./1000 scfm. At a higher water to gas ratio, it is thought that the water *jets* across the throat of the Venturi rather than forming a spray. This *jetting* effect results in lower efficiency due to less intimate contact between the scrub water and the flowing gas stream.

Fig. 4 illustrates the effect of varying the scrub solution temperature on the radioactivity removal efficiencies in the Pease-Anthony Venturi. The Peabody tower was not used in the first series of experiments in order to magnify any change in efficiency resulting from changes in Venturi liquid temperature. In the second series, the scrub solution rate to the Peabody scrubber was constant at 5.5 gal./min.

The use of steam injection to enlarge the particulate by means of the condensation nuclei principle is another variable that was investigated. None of the variables of steam injection were investigated since this was in the nature of a probing experiment to show the feasibility of steam injection. About 190 lb./hr. of steam at 0 psig were introduced into the duct about 12 in. upstream from the Pease-Anthony Venturi throat. The particulate in the gas stream acts as nuclei for the condensing steam and is consequently enlarged by it. This larger particulate is more easily removed by the gas scrubbing equipment.

Gas Flow Rate 285 - 425 S.C.F.M.
Scrub Solution Flow Rate:

Pease-Anthony Venturi	2-13 gal./min.
Schreier-Bartolucci Scrubber	9.0 gal./min.
Peabody Scrubber	5.5 gal./min.

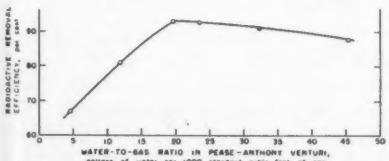
RADIOACTIVE REMOVAL EFFICIENCY, per cent
WATER-TO-GAS RATIO IN PEASE-ANTHONY VENTURI, gallons of water per 1000 standard cubic feet of gas

Fig. 3. Effect of water to gas ration in the Pease-Anthony Venturi on radioactive removal efficiency.

TABLE I
Individual Decontamination Factors

Furnace	2.2×10^2
Schreier-Bartolucci	1.2
Pease-Anthony Venturi—Peabody Couple	50
AEC Filter	2.6×10^3
Overall	3.4×10^7

The results of this experiment are compared with other Venturi scrubbing data in Fig. 4. It appears that the use of steam largely overcomes the effect of scrub water temperature to the Venturi.

The results of varying the number of wetted plates in the Peabody scrub tower was investigated and the efficiency was proportional to the number of wet plates in the range of 0 to 3 wet plates. Since essentially the same result was obtained with either 3 or 4 wetted plates, it appears that 3 is the maximum economical number of plates to be employed.

The heterogeneous composition of the feed material made the determination of particulate or activity removal efficiency of the Schreier-Bartolucci gas scrubber very difficult. From the data amassed, it appears that the efficiency of this scrubber was affected by the type of material charged, and the combustion rate, and varied between 25 and 60%. Filters and organic solids tend to produce a larger particulate while burning, and the larger particulate consequently are more easily removed by scrubbing.

Very little experimental work has been done to determine the overall efficiency of the AEC filter as the designers determined that it was 99.9+% efficient on 0.3 to 1 μ sized particulates. This corresponds to a minimum decontamination factor of 1×10^3.

The efficiency of the filter was checked during one of the high level runs, and an average decontamination value of 2.6×10^3 was obtained. This value corresponds to an efficiency of 99.96%.

The overall decontamination factor reaches a constant value at about 2.3×10^7. This value is substantiated by a cumulative decontamination factor of the individual equipment decontamination factor values.

It is apparent, since under normal operations the exhaust stack gas contains less activity than the natural radioactivity present in the surrounding atmosphere, that a considerably lower efficiency could be tolerated throughout the system. The main value of increasing the overall efficiency is in decreasing the dust load to the AEC filter, thereby increasing its operating life. The experimental work on the Venturi-Peabody couple produced data which enabled the filter life to be extended from one 8-hr. day to five 8-hr. days. The use of steam injection increased the filter life to ten 8-hr. days. This overall increase reduced the cost of filters from $40.00/day to $4.00/day.

At no time during the incinerator operations has there been any evidence of radioactivity buildup or concentration in the system other than in the ash barrel. The level of activity in the system remained fairly constant since the activity was removed from the system in the ash at the same rate that it was added in the charge.

Economics

Incineration is a costly process. It is only justified economically when the cost of storage is high. Rigid control at Argonne National Laboratory of all contaminated wastes has resulted in expensive storage areas. Until recently the solid wastes were stored in carbon steel boxes and these boxes were then placed in wood-covered concrete-lined trenches. The storage costs amount to about $4.00/ft.^{3}, the handling and collection charges are about $5.00/ft.^{3}, making the total cost of solid storage almost $9.00/ft.^{3}. A cost analysis has been made comparing 8-hr. day and 24-hr. day operation of the incinerator. The total processing cost/ft.^{3} for the 8-hr. and 24-hr. day incineration operation are $2.68 and $1.60 respectively. Thus incineration, and the consequent volume reduction of the combustible active wastes resulted in a considerable saving.

Arrangements have now been made to routinely ship wastes in steel bins by rail to Oak Ridge for burial in waste land area. This operation costs about $1.50/ft.^{3} which removes the economic justification for incineration under these conditions. Under other circumstances incineration may be economically justifiable.

Gas Flow Rate 315 S.C.F.M.
Scrub Solution Flow Rate:

Pease-Anthony Venturi	8.0 gal./min.
Schreier-Bartolucci Scrubber	9.0 gal./min.
Peabody Scrubber	0 or 5.5 gal./min.
Steam Injection	0 or 190 lb./hr.

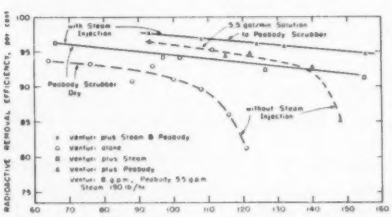

Fig. 4. Effect of steam injection on radioactive removal efficiency by Pease-Anthony Venturi.

Tentative Incinerator Codes, Parts I and II

PART 1. DEFINITIONS AND CLASSIFICATIONS

1.1 Incinerator Terminology

Combustion apparatus in which solid, semisolid, or gaseous combustible wastes are ignited and burned to carbon dioxide and water vapor, and from which the solid residues contain little or no combutible material.

Primary Combustion Chamber

Chamber within an incinerator where primary ignition and burning of the waste occur.

Secondary Combustion Chamber

Chamber connected with the primary chamber where unburned combustible materials from the primary chamber are completely burned.

Drop Arch

Any refractory construction in the primary or secondary chamber that serves to deflect the products of combustion.

Bridge Wall

A partition wall between the primary and secondary chambers over which pass the products of combustion.

Curtain Wall

A refractory construction or baffle, which serves to deflect gases from the primary combustion chamber in a downward direction.

Baffle

Any refractory construction intended to change the direction of flow of the products of combustion.

Checker Work

Multiple openings in a bridge wall, drop arch, or other walls through which the products of combustion pass. The primary purpose is to promote turbulent mixing of the gases.

Grate

Surface with suitable openings, to support the fuel bed and permit passage of air through the burning fuel. It is usually located in the primary combustion chamber, and is designed to permit removal of unburned residue, and may be horizontal or inclined and stationary or movable.

Cold Drying Hearth

A surface within the primary chamber upon which wet waste material is deposited for drying, prior to burning.

Hot Drying Hearth

A surface upon which wet material is placed to dry by the action of hot combustion gases that pass successively over the wet material and under the hearth.

Auxiliary-Fuel Firing Equipment

Equipment to supply additional heat, by the combustion of an auxiliary fuel, for the purpose of attaining temperatures sufficiently high (a) to dry and ignite the waste material, (b) to maintain ignition thereof, and (c) to promote complete combustion of combustible solids, vapors and gases.

Combustion Air

(a) Primary: Air that passes through the fuel bed.

(b) Secondary: Any air, controlled with respect to quantity and direction, supplied beyond the fuel bed, as through ports in the walls or bridge wall of the primary combustion chamber (overfire air) or the secondary combustion chamber, for the purpose of completing combustion of combustible materials in the gases from the fuel bed.

Draft

The pressure difference between the incinerator, or any component part, and the atmosphere, which causes the products of combustion to flow from the incinerator to the atmosphere.

(a) Natural Draft: The pressure difference due to the temperature difference between the flue gases and the atmosphere.

(b) Induced Draft: The pressure difference created by the action of a fan, blower, or ejector, which is located between the incinerator and the stack, or at the stack exit.

(c) Forced draft: The pressure difference created by the action of a fan, blower, or ejector, which supplies the primary combustion air above atmospheric pressure.

Damper

A manually or automatically controlled device used to regulate the rate of flow of air or other gases.

Breeching

A passage for conducting the products of combustion to the stack or chimney.

Breeching By Pass

An arrangement of breeching and dampers to permit the intermittent use of 2 or more passages for products of combustion to the stack or chimney.

Fly Ash

Suspended particulate matter in products of combustion.

Fly-Ash Collector

A device designed to remove fly ash from products of combustion by electrical or mechanical means.

Flue Gas Washer or Scrubber

Equipment designed to remove fly ash, odorous compounds, and other objectionable materials from products of combustion, by means of sprays, wet baffles, etc.

Settling Chamber

Chamber designed to reduce velocity of gases sufficiently to promote the settling of fly ash.

Stack or Chimney

A vertical passage for conducting products of combustion to the atmosphere.

Spark Arrester

A screen to prevent sparks, embers or other ignited material above a given size from being expelled to the atmosphere.

1.2 Classification of Combustible Wastes

Type 1: Rubbish, consisting of combustible waste such as paper, cartons, rags, grass cuttings, leaves, wood scraps, saw dust, and floor sweepings from domestic, commercial and industrial activities. This waste may contain up to 10% incombustible solids, up to 25% moisture, and have a heating value between about 5500 and 8500 Btu./lb.

Editor's Note: This the second publication of a report from the Technical Coordinating Committee. This is a *tentative report* at this time and does not commit the Association to underwriting the report or giving to it any authoritative connotation.

Referring to the By-Laws of the Association, in Article XV we find the procedure for handling technical coordinating committee reports as follows:

Section 4. Upon completion of the task of any subcommittee, its recommendations shall be submitted to the Technical Coordinating Committee for study and coordination . . . and, if approved by this committee and the Board, the report shall be pubished in the next issue of the *Journal* for consideration of the membership. Constructive criticism of the report shall be invited and given to the subcommittee for its consideration. If advisable, the subcommittee shall re-submit its amended report to the parent committee . . .

Part I of this report was submitted to the Technical Coordinating Committee on June 20, 1955 and Part II on August 5, 1955. Comments, corrections and additions, deletions, etc., were added to the report. It was then submitted on March 1, 1956, to the Board of Directors who have authorized publication in the *Journal* as a tentative report.

Kindly direct your comments or criticism to the office of the executive secretary before May 1, 1957, for consideration by the Incinerator Committee, T-2. 1.

Type 2: Refuse, consisting of approximately equal weights of rubbish and garbage common to apartment and residential occupancy.

Type 3: Garbage, consisting of animal and vegetable wastes from restaurants, cafeterias, hotels, hospitals, markets, and like installations. This waste may contain up to 85% moisture, up to 10% incombustible solids, and have a heating value as low as 1000 Btu./lb., as fired.

Type 4: Human and animal remains, such as carcasses, organs, and solid organic wastes from hospitals, laboratories, abattoirs, animal pounds and similar sources.

Type 5: Gaseous, liquid, and semi-liquid by-product wastes from industrial operations and includes noxious or toxic materials, such as tar, paints, solvents, and fumes from cooking processes. The heating value will depend upon the individual materials that are handled.

Type 6: Solid by-product wastes, such as rubber, plastics, wood waste, and noxious or toxic materials from industrial operations. The heating value will depend upon the individual materials that are handled.

1.3 Classification of Incinerators

Class I

Portable, packaged, completely assembled, direct fed, not having over 5 ft.^{3} storage capacity (or 25 lbs./hr. burning rate) suitable for Type 1 or Type 2 waste.

Class IA

Portable, packaged or job assembled, direct fed, having over 5 ft.^{3} but not exceeding 12 ft.^{3} storage capacity, (or 25 lbs. to 75 lbs./hr. burning rate in primary combustion chamber,) suitable for Type 1 or Type 2 waste.

Class II

Flue-fed suitable for Type 1 or Type 2 waste.

Class III

Direct-fed, over 12 ft.^{3} storage capacity (or 75 lbs./hr. burning rate) for Type 1 or Type 2 waste.

Class IV

Same as Class III, but suitable for Type 3 waste.

Class V

Municipal.

Class VI

Crematory and pathological units, for Type 4 waste.

Class VII

Equipment for Type 5 or Type 6 waste.

PART II. TENTATIVE CODE FOR FLUE-FED INCINERATORS

2.1 General

A flue-fed incinerator is designed to burn Type 1 or 2 waste, which is fed from one or more floors above the combustion chamber. This type of incinerator is not recommended for use in schools, hospitals, or other public buildings.

2.2 Permit

A permit shall be obtained from the proper municipal authority before any installation or major repair is made which involves any alteration in the original design of an incinerator. Required fees shall be paid to proper authority to cover the cost of issuing the permit and making the necessary field inspections.

2.3 Plans and Specifications

Plans, specifications, and design data shall be on file in the office of the proper municipal authority for all standard incinerators. For special designs complete plans, specifications, and design data shall be submitted for approval before any installation shall be made.

2.4 Name Plate

Each incinerator shall be provided with a metal plate permanently attached in a conspicious location. The plate shall bear the manufacturer's name, the trade name of the incinerator, the model number, the rated capacity of the unit and the type of waste for which it is designed.

2.5 Location and Mounting of Incinerator

(a) Incinerators shall be set on proper foundations on the ground or on fire resistive floors with no combustible material on the underside thereof.

(b) Incinerators in which the combined hearth and grate area of the combustion chamber is 7 ft.^{2} or less should be enclosed within a room separated from other parts of the building by walls and ceiling having a fire resistance of not less than 1 hr., as required by the National Board of Fire Underwriters, and used for no other purpose except storage of containers of waste materials and refuse to be burned, and building heating equipment. In private dwellings occupied by not more than 2 families, enclosing walls may be omitted, provided minimum clearances prescribed for Domestic Type incinerators are provided.

(c) Incinerators in which the combined hearth and grate area of the combustion chamber exceeds 7 ft.^{2} shall be enclosed within a room separated from other parts of the building by walls, floor or ceiling having a fire resistance of not less than 2 hrs., as required by the National Board of Fire Underwriters, and used for no other purpose except storage of waste material and refuse containers, and building heating equipment.

(d) Doors or other openings in rooms containing incinerators communicating with other areas of the building shall be protected by approved self-closing or automatic fire doors suitable for Class B situations.

(e) The incinerator shall have clearance in front of the firing and cleanout doors equal to the inside depth of the combustion chamber plus the thickness of 1 wall, but in no instance less than 5 ft.

(f) The incinerator room shall be adequately lighted with the switch located outside of the room at the opening side of the door.

(g) Rooms containing incinerators shall be supplied with an adequate amount of air for combustion and ventilation. Air supply may be furnished by one of the following means:

1. A louvred opening or other suitable air intake not communicating to other parts of the building.
2. A duct leading from the incinerator room to the outside air.
3. A duct leading to a boiler or furnace room cut off as prescribed above and provided with sufficient air supply for both rooms.
4. The free area of any duct or opening shall not be less than the flue area unless a fan is provided.

2.6 Furnace Construction

(a) An incinerator furnace shall be built with not less than 4-½ in. refractory walls in accordance with accepted furnace construction practice. The exterior walls of the furnace shall be not less than 4 in. of common brick. In lieu of common brick a steel jacket protected by at least 2 in. of approved insulation may be used.

(b) Other constructions may be used if equivalent to the construction outlined in the preceding paragraph, in structural strength, insulating value and ability to withstand thermal expansion and flame impingement.

(c) Fire brick shall be laid in high temperature cement or fire clay mortar. All common brickwork shall be laid with full, push filled, cross and bed mortar joints.

(d) No metal stays, lintels not part of a door frame casting, or other supports shall be exposed to the interior of the furnace or the products of combustion.

2.7 Furnace Design

In accordance with laws and regulations pertaining to smoke and air pollution in effect in most cities, incinerators shall be so designed and constructed that there will be no discharge of objectionable smoke, odors, or fly ash, resulting from their operation in violation of existing regulations. In order to accomplish this result and for the purposes of these rules the design shall conform to the following minimum requirements:

(a) Volume of combustion chamber above the grates shall be not less than 4 nor more than 6 ft.^{3}/ft.^{2} of grate area.

(b) Grate area shall be calculated on the basis of 0.15 ft.^{2} of grate area/sleeping room, but in no case shall the total grate area be less than 4 ft.^{2}. Horizontal cross-sectional area of the combustion chamber shall be considered to be the grate area, including both the iron grate and any solid hearth that is used. The area of inclined or step grates shall be computed on the basis of the projected horizontal area.

(c) Grate design shall provide at least 40% open area for admission of primary air, no more solid hearth than 25% of the total grate area, and an arrangement for dumping and locking, except that non-dumping grates may be used if they are on the same level as the firing-door sill.

(d) Temperature of products of combustion shall be not less than 1200°F where they enter the flue.

2.8 Auxiliary Burners

(a) Each incinerator shall be provided with one or more approved gas or oil burners for the purpose of drying the charge and supporting combustion.

(b) The burner or burners shall be of such capacity and type so located that smoke and odors will be controlled within the limits as approved by the air pollution abatement official. Recommended capacities are as follows:

Up to 8 ft.^{2} grate area not less than 25,000 Btu./hr.

Up to 12 ft.^{2} grate area not less than 600,000 Btu./hr.

Up to 18 ft.^{2} grate area not less than 1,000,000 Btu./hr.

(c) The burner or burners shall be located in the primary combustion chamber or in a secondary chamber or in both. When located in a wall of the primary chamber, a burner shall be adjusted to produce a flame length equal at least to ¾ the distance to the opposite wall. The secondary chamber may be a part of the incinerator proper or it may be a part of a roof settling chamber as may be most advantageous.

(d) Each burner shall be provided with a gas-electric pilot and an approved automatic device, which will furnish protection in case gas flame is accidentally extinguished.

2.9 Service Openings

(a) The clear area of each service opening into the incinerator flue shall not exceed ⅓ of the cross-sectional flue area.

(b) All service openings into an incinerator flue shall be provided with an approved metal charging door so designed that the opening to the stack will be closed off when the door is fully opened for charging. A metal frame shall be firmly attached to the masonry. The door shall be built or counter weighted in such a manner that it will close automatically when released. No portion of the door or door frame shall project into the flue.

2.10 Vestibule or Compartment

(a) When a charging chute opens upon a hallway, stair landing or any interior portion of a building, a vestibule or compartment shall be provided to enclose the service opening. This compartment shall not be less than 24 in. in depth and shall be provided with at least a Class C fire door.

(b) Each such compartment shall be ventilated by means of a continuous duct run to the roof and there provided with an exhaust blower capable of removing any smoke or odors from the compartment. The motor starting switch shall be located at the incinerator.

2.11 Stack

(a) No boiler, furnace, water heater, stove, appliance of any description, duct or vent shall be connected to or discharge into the incinerator stack.

(b) The stack shall be built in accordance with the provisions of the building code of the jurisdiction in which the incinerator is located and the structural properties shall be approved by the appropriate engineer handling such work.

(c) The stack shall be constructed straight and plumb with no offsets or restrictions at any point, and shall be finished smooth on the inside with no projections of mortar, brick or other material, nor shall there be any offsets below the top hopper door.

(d) A steel ladder shall be attached to the side of that portion of the stack extending above the roof.

(e) The inside size of incinerator flues shall not be less than the following:

1. For 1, 2 and 3 story buildings: 18 in. by 18 in.
2. For buildings in excess of 3 stories: 22.5 in. by 22.5 in.

(f) Two-flue or so-called divided-flue incinerators having 1 flue for feeding waste and 1 for discharging combustion gases may be installed provided that the feeding flue is kept in a sanitary condition, free from odors or vermin, and the type of construction of both flues is the same as for a single-flue incinerator.

2.12 Height of Stack

In designing and locating an incinerator stack the following factors must be taken into consideration: The height and location of adjacent buildings, the height of the building in which it is located, the type of terrain, the location of windows, ventilating ducts, air intakes and any other factors which may cause the products of combustion to enter or be deflected into any building or area, thereby creating a nuisance or hazard.

(a) An incinerator stack on any building other than a private residence shall not be less than 40 ft. above grade and in no case less than 15 ft. above the roof of the building in which it is located.

(b) A stack shall be at least 5 ft. above the top of any parapet, penthouse, machinery or boiler room, or other obstruction on the building in which it is located.

(c) A stack shall be at least 5 ft. above the highest point of any adjacent building or natural objects.

(d) The stack shall be located so that its discharge will not enter or be drawn into any intake, ventilating duct, window or opening so as to become a nuisance or hazard.

2.13 Spark Arrester

Each stack shall terminate in a substantially constructed screen or spark arrester which shall be made of 16 gage wire having openings not greater than ¼ in. The wire shall be attached to an angle iron frame which shall be permanently attached to the stack. The height of the screen shall not be less than the largest stack dimension. A solid metal top sloping toward the sides not less than 15 degrees shall be provided. The entire screen shall be made so that there are no cracks or openings in it and shall be tightly sealed to the masonry. Any other type of screen shall be submitted for approval and if considered to be equal or superior to the above may be approved for trial.

2.14 Settling Chambers

All flue fed incinerators shall be equipped with an approved means for the removal of objectionable fly ash from the exit gases.

(a) Buildings over 3 stories in height shall be provided with an approved settling or expansion chamber, except that any other equivalent method of removing fly ash to the satisfaction and approval of the official in charge of air pollution abatement may be used, such

as reverse flow baffling, washers, collectors or other means.

(b) Equipment or rooms for the separation of fly ash from the exit gases may be located either in the basement or on the roof. A settling chamber shall not be located on a roof unless there are satisfactory means of access to the roof and chamber.

(c) Where fly ash accumulates, means shall be provided to wet it before it is removed from the collection point.

(d) Settling chambers shall be of masonry or metal construction and shall comply with all provisions of the building code in the jurisdiction where used.

(e) Each roof settling chamber shall have an easily-accessible, tight-fitting metal door, stiffened against warping, and with a handle so arranged that it can only be latched from the outside. The bottom of the door opening shall not be more than 18 in. above the floor of the chamber.

(f) No ducts, pipes, wires, or other extraneous equipment shall pass through, discharge into or be located in a settling chamber.

(g) The gas inlet opening from the stack into the settling chamber shall be at least 50% greater than the area of the stack, with the lower edge of the opening 18 in. above the floor. The stack shall be permanently blocked off at the upper edge of the opening and the turn where the gases enter the settling chamber from the stack shall be a long radius turn or shall have turning vanes to provide smooth gas flow. The gas exit opening shall be on a side of the chamber other than the inlet. The area of the exit opening and the stack above shall be at least 50% greater than that of the main stack. The top of the stack shall be not less than 15 ft. above the floor of the settling chamber, giving full consideration to the maintenance of adequate draft on the upper floors of the building and to the provisions of Section 2.12.

(h) The inside height of a settling chamber shall be not less than 6 ft.

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Continuous Flow Method

(Continued from page 40)

and intake air, equals essentially the volume flow of dried exhaust.

Hydrocarbon mass flow data obtained by means of the infrared analyzer and air flow meter on a series of road tests are shown in Table V. The concentration of C_{3+} hydrocarbons obtained from the analyzer in mole percent is converted to lb./ft.^{3} of dried exhaust. Hydrocarbons in lb./ft.^{3} multiplied by the flow of dried exhaust gas in ft.^{3}/hr. gives the emission of C_{3+} hydrocarbons in lb./hr.

Conclusions

Infrared analysis of exhaust gas by means of interference filter photometry offers a convenient way of studying combustion characteristics of automotive engines. Particularly, the composition of engine exhaust in respect to the C_3 and higher fuel components can be readily monitored in a moving vehicle. Analytical results obtained by means of the interference filter photometer correlate well with those obtained by means of more elaborate instruments.

Simultaneous measurements of hydrocarbon concentration and air flow on moving vehicles provides a convenient means of determining hydrocarbon emission in terms of wt./unit time for any given road operating pattern.

TABLE V

C_3 and Higher Hydrocarbon Mass Flow Data Obtained with Infrared Interference Filter Analyzer and Road Air Flow Meter on a Moving Car

Driving Condition	mph.	Dry Exhaust at 79°F ft.^{3}/hr.	Exhaust C_{3+} Hydrocarbons lb./ft.^{3}	lb./hr.
Cruise	10	1000.	0.000121	0.12
Cruise	20	1300.	0.000116	0.15
Cruise	30	2200.	0.000094	0.21
Cruise	40	2900.	0.000068	0.20
Cruise	50	3800.	0.000064	0.24
Cruise	60	4900.	0.000057	0.28
Idle	0	600.	0.00032	0.19
Deceleration (Maximum concentration after closing throttle at 40 mph.)	..	640.	0.0017	1.1
Acceleration:				
Wide Open Throttle	30-90	(avg.) 8000.	0.00014	1.1
Wide Open Throttle	90	(about) 13000.	0.00030	3.9

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Electric Furnace Ferrosilicon Fume Collection

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because of plugging. A variety of packs were tried but none could be successfully maintained at constant resistance.

The most efficient pumping and nozzle arrangement found was the use of a high pressure fog nozzle operating at 400 psi water pressure. Air-jet and pneumatic nozzles were tried but were found either uneconomical or unsuited for satisfactory performance. The wet collection unit was found to satisfactorily lower gas temperatures and appears to have promise for the collection of soluble fumes. In this instance, it recovered ferrosilicon fume at an efficiency of 70%, but a considerable carry-out of water and overall water consumption was entailed.

On a basis of this investigation, it was concluded that the wet collection unit is not satisfactory for high efficiency removal of ferrosilicon fume without a secondary collector. It may be suitable for other ferroalloy fumes of larger particle size from other electric furnace operations.

The result of the study on a dry collection unit utilizing the reverse-jet principle indicated that it was possible to obtain satisfactory performance with aid dilution, spray cooling, or the high temperature-resistant medium. The capacity of the unit varied with the type of air pretreatment employed. With any of the three methods investigated, efficiencies well over 99% were obtained with operating resistance of approximately 6 to 7 in. of water. The maximum capacity with air dilution was approximately 15 cfm./ft.^{2} of bag, with spray cooling approximately 9½ cfm./ft.^{2} cloth, and the high temperature medium utilizing Orlon-Fiberglas layer quilted medium without auxiliary cooling gave a value of 7.4 cfm./ft.^{2} cloth area.

On a basis of these tests, it is felt that a dry collection unit with high temperature-resistant medium indicates the most promise for direct application to fume recovery of ferrosilicon electric furnaces.

A study of other types of wet units which could be applied indicated that the unit studied had performance comparable to any other units now available. In the case of dry filtration, the reverse-jet unit provided a nearly constant resistance device at high air flow capacities. Although wool cloth shaking-type bags, such as are used in smelters with dilution air or water spray cooling for temperature control, should give comparable efficiencies, they would require much larger size bag installations because of the 2 cfm. or less/ft.^{2} requirement in capacity.

Acknowledgments

The authors wish to express their appreciation for the technical assistance and cooperation rendered by the following people who assisted in this study: Roy P. Warren and Robert De Benham of the Buffalo Forge Co., Theodore Place and David Henthorn of the Vanadium Corp. of America, and Charles E. Billings of the Air Cleaning Laboratory, School of Public Health, Harvard University.

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Engine Air Flow Measurements

(Continued from page 37)

based on simultaneous operation in series with standard dynamometer air flow measuring equipment.

If an instrument of 1 or 2% accuracy is desired, a more critical look must be taken at the effects of water vapor, pulsations, and dirt accumulation. No indication of inaccuracy was obtained; however, the effects of these variables would have to be further investigated before a definite accuracy could be stated for any particular application.

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Atmospheric Diffusion Formulae

(Continued from page 13)

generally be obtained, although a formidable list of modifying and qualifying factors must be considered. Reliability of the results is too variable for a single specification, but it certainly approaches ± 50% for simpler cases.

The treatment of particulate deposition is a far more complex problem in which our knowledge is severely limited. The reliability of theoretical estimates for small particles is unknown.

Removal of Halogens, Carbon Dioxide and Aerosols

(Continued from page 20)

ing to First[5], whereas filters usually have efficiencies greater than 95%.

Just as in vapor absorption, it is important to have a material transfer coefficient independent of contact time to serve as a measure of absorption capabilities of the equipment. Such a coefficient is defined by

$$vGdC = -K_c a\, C\, dH,$$

where

C = the number of particles/ft.^{3} of the air stream in the differential element of length dH
H = the length of the tower, ft.
G = the mass velocity of the air stream —lbs./(hr.) (ft.^{2})
v = specific volume of the air stream, ft.^{3}/lb.
$K_c a$ = the material transfer coefficient, 1/hr.

In this expression, the transfer rate is expressed as particles/hr./ft.^{3} of tower volume and the driving force is in particles/ft.^{3} of air; this leaves the net units of $K_G a$ as merely reciprocal hours. The integrated form for air at 70°F and 1 atm. is

$$K_c a = \frac{30.8G}{H} \log \frac{C_1}{C_2}$$

The $K_c a$ values were shown to be roughly independent of gas rate and contact time. However, the effects on $K_c a$ of concentration, liquid rate, and particle size were not separated in this study. It would be expected that $K_c a$ would show a slight increase with particle concentration and a strong increase with liquid rate. The concentration can also be expressed as mass (of particles)/ft.^{3}. Calculated values of mass concentration are also shown in Table III.

Conclusions

For a range of inlet concentrations of bromine fluorides and iodine up to 690 ppm. (wt.), efficiencies of absorption ranged from 69 to 100%, the lower figures being those for the bromide component. Although there was some scattering of the data, most of the runs showed absorption efficiencies above 95%, which is considered adequate for safety in the 6000 ft.^{3}/min. ventilation system in which the scrubber is installed. The average $K_G a$ for absorption of the above halogen is 11.5 lb.-mols./(hr.) (ft.^{3}) (atm.). The corresponding average gas rate was 1442 lb./hr./ft.^{2}; the liquid rate, 112 lbs./(hr.) (ft.^{3}). The $K_G a$, and hence the absorption efficiency, increases with inlet concentration to about the 0.7 power, a fact which provides a safety factor.

The above $K_G a$ values are consistent with those of earlier halogen absorption work in a single spray tower[1].

Absorption of atmospheric carbon dioxide was performed over a range of gas rates, liquid rates, potassium hydroxide concentrations, and carbon dioxide concentrations. The tower is capable of giving a $K_G a$ greater than 3 lb.-mols./(hr.) (ft.^{3}) (atm.) using a 10% potassium hydroxide solution as the absorbing liquid. In general the values of $K_G a$ for carbon dioxide absorption were of the same magnitude as those obtained under absorption under approximately similar conditions in a packed tower of 1 ft. diam. and 7.8 ft. height.

The carbon dioxide runs indicated the effect of process variables on $K_G a$. $K_G a$ increased (1) with the 0.8 power of carbon dioxide concentration and (2) with the 1.6 power of the liquid rate. (3) The $K_G a$ increased rapidly with potassium hydroxide concentrations up to 10% (wt.); the rate of increase above 10% was slower. (4) There was no appreciable effect of gas rate on $K_G a$.

Aerosol removal runs were made for 2 ranges of particle sizes; the mean diam. were 0.5 and about 0.10 μ. The removal efficiencies were between 35 and 57%. A material transfer coefficient analogous to $K_G a$ was calculated for aerosol removal, and this coefficient appeared to be independent of the gas rate. Hence, it is possible that higher removal efficiencies could be achieved by lengthening the residence time of gas in the scrubber.

The spray tower showed absorption performance that is comparable to packed towers, and has a wide range of possible applications, especially where simplicity, low weight, and low gas pressure drop are important.

[1] See footnote 1, page 19.

TABLE III
Removal of Aerosols In A Spray Tower

Run	1	2	3
Length of Tower, ft.	15	15	10
Aerosol	NH_4Cl	NH_4Cl	Na_2O
Mean Particle Diam., Microns	0.5	0.5	0.1
Gas Flow, lb./(hr.)(ft.^{2})	900	1250	460
Liquid Flow, lb./(hr.)(ft.^{3})	109	109	150
Residence Time, sec.	4.48	3.21	5.83
Inlet Conc. Particles/ft.^{3}	79 x 10^6	107 x 10^6	511 x 10^6
Inlet Mass Conc.,[a] gm./ft.^{3}	805 x 10^{-7}	1135 x 10^{-7}	4 x 10^{-7}
Exit Conc., particles/ft.^{3}	34 x 10^6	60 x 10^6	333 x 10^6
Efficiency of Removal, %	57	44	35
$K_c a$, (hr.$^{-1}$)	680	648	265

[a] Assuming spherical particles.

Acknowledgment

The aerosol measurements were greatly facilitated by the cooperation of Donald P. O'Niel of the Industrial Hygiene and Safety Division. Lester F. Dorsey of the Chemical Engineering Division assisted in all phases of the experimental work. Analysis of aqueous halide solutions was done by the analytical section of the Chemical Engineering Division.

Response of Plants to Air Pollution

(Continued from page 9)

materials and a number of dithiocarbamates as well as tetramethyl thiuram-disulfide gave excellent localized protection. This discovery not only is of practical importance in providing relief to the producer of plants sensitive to air pollution injury, but also gives further support to the concept that the principal toxicants are oxidants. Zinc ethylene bisdithiocarbamate not only protects plants from injury attributable to the reaction products of ozonated olefin, but to that attributable to ozone as well. It is hoped that further investigation will provide the necessary information on methods for applying material to field grown crops. Glasshouse-grown crops can be protected from damage by passing the air through activated-carbon filters. If a facility is not available for air purification protection to glasshouse crops, perhaps it can be afforded through the application of the dithiocarbamates and thiuram.

In conclusion it may be said that several millions of dollars are annually lost because of direct injury to the saleable portions of agricultural commodities produced in California. In addition, there is suppression of growth and reduction in yield without the presence of visible injury symptoms. Economic loss due to growth suppression has not been determined. Exposure of plants to oxidants affects such biological processes as cell permeability, water movement, respiration, photosynthesis, and possibly enzyme systems. The response of plants to air pollution depends upon the type of pollutant present, its concentration, and the length of exposure to it. The response of plants to the new class of toxicants known as oxidants is distinctly different than that attributable to fluorides, sulfur dioxide and halogens. The specific symptoms incited by exposure to oxidants can be used to determine the presence of ozonated olefins and ozone in polluted air masses. This response provides an excellent bio-assay system for determining areas affected by pollution. Not only are areas clearly delineated, but the plant provides a specific response to 2 kinds of oxidants that cannot be readily separated by the usual chemical monitoring systems. Oxidant levels reported in the Los Angeles and San Francisco areas as due principally to ozone cannot be confirmed on the basis of plant response since the symptomatology is specifically that of oxidized hydrocarbons and not that of the oxidant ozone. The inclusion of a biological assay system provides a more intelligent and comprehensive assay method for determining the distribution and constitution of modern urban pollution levels.

Acknowledgment

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Effect of Aircraft on Airport Visibility

(Continued from page 10)

cesses on visibility. Twomey[6] has found that certain atmospheric nuclei, apparently produced by man-made contamination, become droplets at a relative humidity between 80 and 82%.

In Japan, Ogiwara and Okita[7] made a study of haze particles under an electron microscope. They found that hazes consist equally of hygroscopic and non-hygroscopic particles, mainly originating in combustion processes. The hygroscopic nuclei would grow at the high relative humidities existing at Goose Bay during the critical period, further restricting visibility. Little sea salt was found in the hazes over Japan. Other investigators have found sea salt to be the most common nucleus, but that under conditions of the problem under discussion here, combustion could become very important. With regard to his investigations over England, Best[8] stated that "the effect of combustion nuclei is negligible unless they are extremely numerous, but the concomitant smoke particles contribute largely to impairment of visibility and when plentiful may even produce thick fog."

In view of these findings, it appears that in the case under study, conditions were ideal for combustion to produce a haze, which probably went unreported because of the light snow. Great quantities of smoke and other nuclei were produced by incomplete combustion in the landing aircraft. At the same time the wind speed fell from 3 knots to calm. Even a light wind, such as 5 miles/hr., would move polluted air a distance of a mile in 12 min., quickly clearing an airstrip of all locally produced contamination. The associated turbulence would also aid dispersal through increased diffusion. But in calm conditions, pollution tends to remain in the source region. The raobs show great stability in the lower levels, hence all particulate matter would be trapped in the surface layer. Finally the relative humidity was high—between 84 and 88% — which would enable growth of the hygroscopic particles to further restrict the visibility.

The fact that the weather conditions improved a short time later with no apparent change in the meteorological parameters lends added weight to the assumption that the unfavorable conditions had been caused by a phenomenon of a temporary nature, such as the introduction into the air of smoke particles and nuclei. With no new nuclei being added after the 3 flights of F-86's landed, the haze would gradually dissipate through diffusion, settling, and by a washing out of the air by the falling snow flakes.

Conclusions

Under certain meteorological conditions, the smoke particles and hygroscopic nuclei contained in aircraft exhaust can result in a serious deterioration of the weather, especially visibility, over an airfield. The responsibile conditions are stability in the lower atmosphere, calm or very light winds, and high relative humidities. Except for absence of a saturation requirement, these conditions are rather similar to those giving rise to radiation fogs.

[6] Twomey, S., "The Composition of Hygroscopic Particles in the Atmosphere," *J. Meteor.*, **11**, 334-338 (1954).

[7] Ogiwara, S., and Okita, T., "Electron-Microscope Study of Cloud and Fog Nuclei," *Tellus*, **4**, 223-240 (1952).

[8] Best, A. O., "Condensation Nuclei and the Development of Radiation Fog," *Quart. J. Roy Meteor. Soc.*, **79**, 112-120 (1953).

Control of Gob Pile Fires

(Continued from page 31)

play an immensely important role in the problems of air pollution. The smoke and gases released from a burning gob pile are more or less at ground level. They are not lifted into the atmosphere through the agency of chimneys. In addition, there is nothing to create the gas velocity attained in modern chimneys. And whereas a chimney is what may suitably be described as a *point source*, the smoke released from a gob pile frequently comes from a rather large area. Under such circumstances the performance of gob pile atmospheric pollution control will vary with the type of local weather being experienced in the gob pile area.

On a windy day accompanied by considerable turbulence in the air, the release from the refuse piles is rapidly carried up aloft and dissipated in a vast volume of the atmosphere. Great dilution is thus brought about, and the general impression on the average person is a gratifying one.

When a calm exists, however, and there is no scavenging effect of air movements toward the upper layers of the atmosphere, the general observer may feel that more effort should be made.

Actually, the success of gob pile fire control is the same in both cases. It is purely a matter of meteorological conditions. In other words, "let's blame it on the weather."

Effect of Topography on Winds and Diffusion Conditions at NRTS

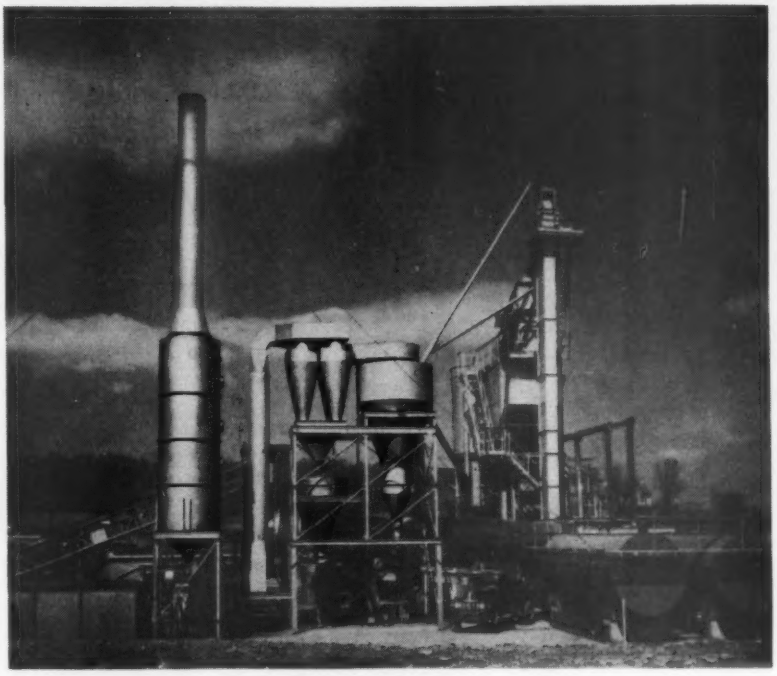
(Continued from page 16)

they will be a detriment to diffusion, but they may cause considerable difficulty for operations requiring a forecast of winds from a certain direction. The possibility of recirculation of effluent, inherent in mountain-valley breezes and standing eddies, is of no concern for anticipated operational effluent releases, but must be taken into account for disaster planning.

Acknowledgment

The author is indebted to Daniel M. Morgan for the preparation of the illustrations, and to the other personnel of Weather Bureau Office, Idaho Falls, Idaho, for assistance in the collection and analysis of data.

ONE OF A SERIES SHOWING DUCON COLLECTION UNITS IN ACTION



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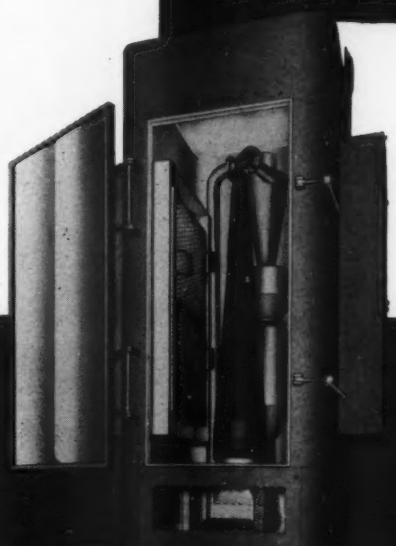

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How the Steel Industry Is Fighting Air Pollution

When the public hears about dust and fume control it is often in terms of what has *not* been done. It is important that they should also know what *has* been done, because the record of the steel industry is one of the most progressive.

The purpose of this discussion is to give the executives the facts to prove this point.

Q. *First of all, how can you measure the progress of dust and fume control in the iron and steel industry?*

A. As you know, there are many ways to combat air pollution. Equipment and methods vary in effectiveness, but the industry agrees that electrical precipitators have the highest collection efficiencies. By keeping track of the demand for this high efficiency equipment over the years, we can get a good indication of the importance the industry places on dust and fume control and the progress they are making.

Q. *Do these figures show an increasing interest in this high efficiency equipment?*

A. Suppose we let the figures speak for themselves. Since 1945 precipitator capacity in the steel industry had a greater increase than in any previous ten year period. Precipitators handling about 6½ million cfm were installed during this period.

Q. *But can't you attribute this growth to the increase in steel-making capacity?*

A. Some of this growth is due to expanded production facilities, but that's just a part of it. For instance, iron and steel production has increased about 30% since 1945 — but precipitator capacity has increased about 130% during this same period.

Q. *In the old days, I guess precipitators were used primarily in blast furnaces, weren't they?*

A. That's right. The first one went into operation in 1930. Since then, 169 Research Cottrells have been ordered by the industry.

Q. *What about new applications?*

A. We have a number of new uses that have proven themselves on the job. Open hearths, for instance. In one installation, our precipitators reduced stack discharge to a little over 2 pounds per hour. That's quite a reduction when you consider that the discharge without a precipitator ranged from 75 to 245 pounds per hour.

Q. *I understand your Cottrells are used on some sintering machines now. Is this true?*

A. Yes, we have three in operation and more under construction.

Q. *How about scarfing machines?*

A. This is a recent application which has worked out very satisfactorily. Two precipitators are now in operation on this application.

Q. *Has anything been done on such problems as iron cupolas, electric furnaces, and ferromanganese blast furnaces?*

A. Yes. Installations have been made on all these problems.

Q. *How do you go about developing these new applications?*

A. We work very closely with our customers on these new projects. Our laboratory is a big help, and our 40 years of pilot plant experience plus over 2,000 precipitators give us the kind of experience that leads to the successful engineering of projects like these.

If you would like to have more information about these applications, or if you want to investigate the possibility of using precipitators on other equipment, our nearest representative will be glad to call on you.

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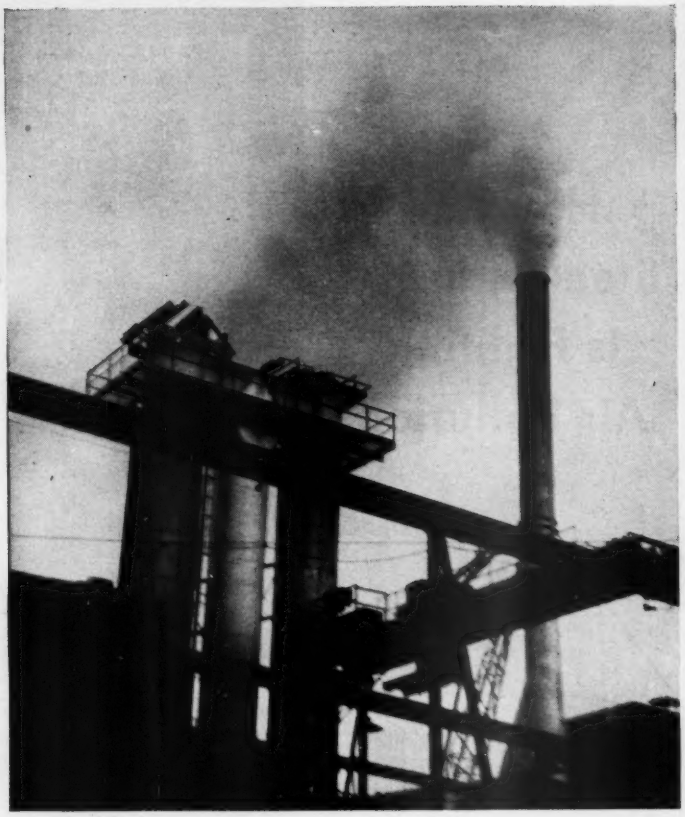

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